



# *Mars: An Enigmatic Planet*

*Richard W. Zurek*

*Chief Scientist, Mars Program Office*

*Jet Propulsion Laboratory*

*California Institute of Technology*

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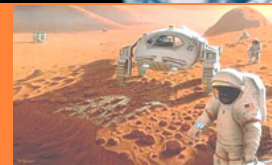
*Government sponsorship acknowledged.*

# ***Why Explore Mars?***

Did Life ever arise on Mars?  
If so, is it still there?

Was the early climate more Earth-like? Why has it changed?

Mars: A destination for  
human exploration?





# ***Mars Exploration***

We can look for life, but where & when?

- Start with habitability
- Where is the evidence preserved?

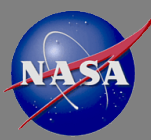
Planetology: How do planets form and change with time? What is the future of the Earth? Takes all disciplines...

- Where is the evidence of change preserved?
  - What are the processes of change?
  - How rapidly can change occur?

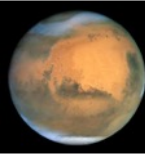
When studying the other planets, how do we go beyond our Earth experience (bias)?

Mars: What do we need to know before humans go there?





# Lowellian Mars



Mars Exploration Program

## Mars was an older Earth

- Similar Length of Day
- Land Area ~ Earth's
- Polar Caps
- Seasonal “Wave of Darkening”



Percival Lowell's Mars:

*An Active Water Cycle*

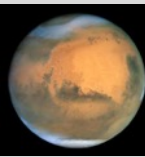
*A Thick Enough Atmosphere ( $\geq 10\%$  of Earth's)*

*An Abode of Life (& Intelligent Life at That!)*





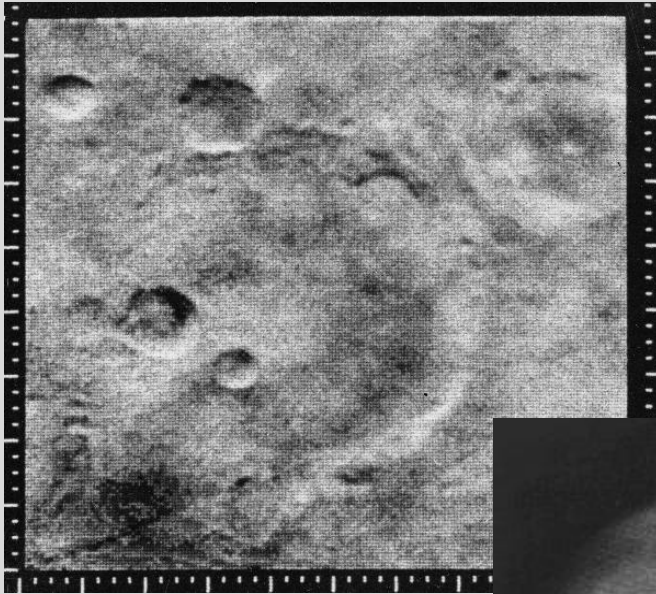
# Early Views from Space



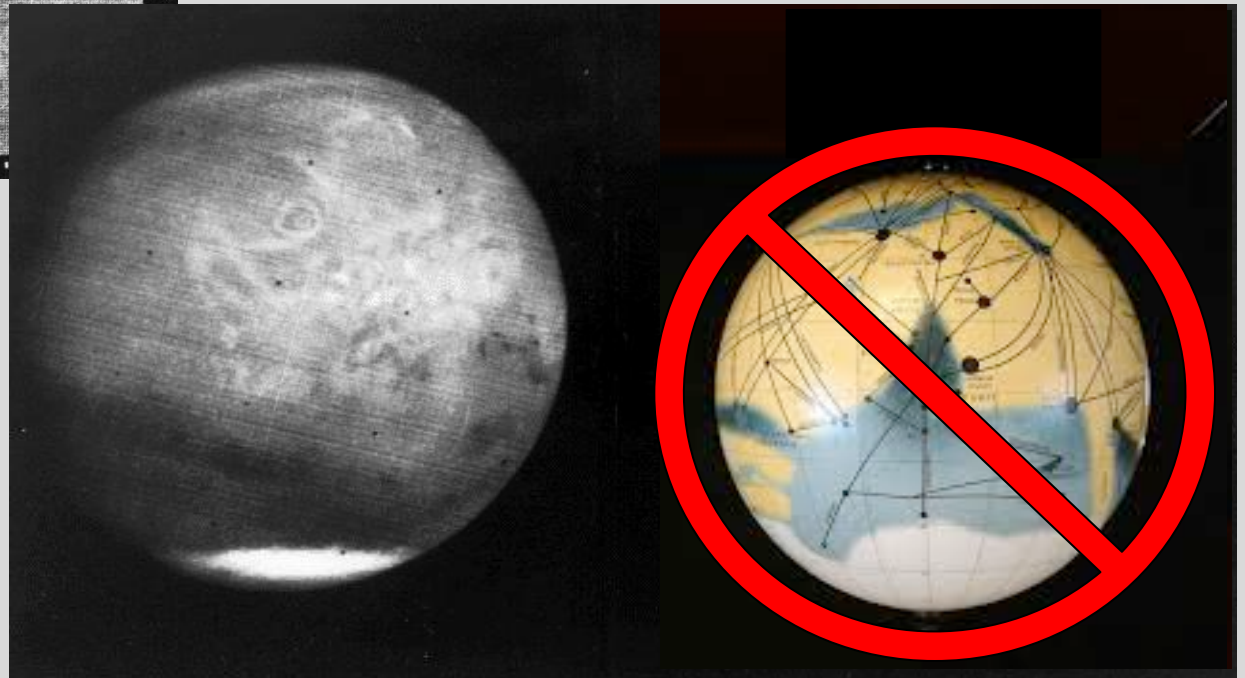
*Mars Exploration Program*

**1965: Mariner 4 photos  
reveal a moonscape**

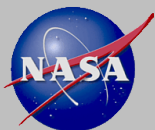
**1969: Mariner 6 & 7  
show a heavily cratered  
Southern Hemisphere**



**Mariners 4 & 7  
CREDIT: NASA / JPL**

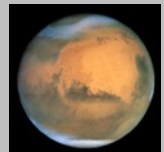




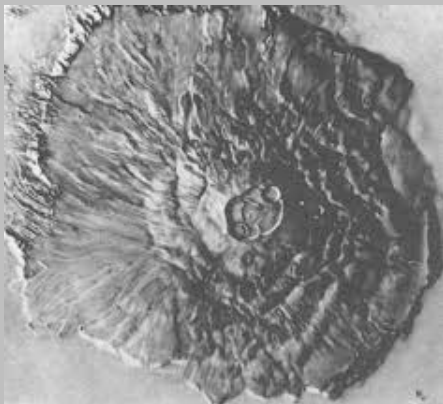
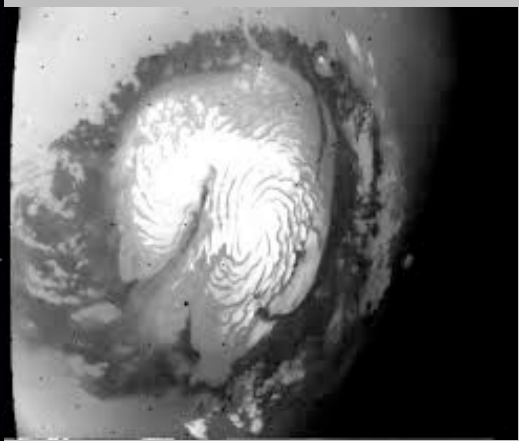
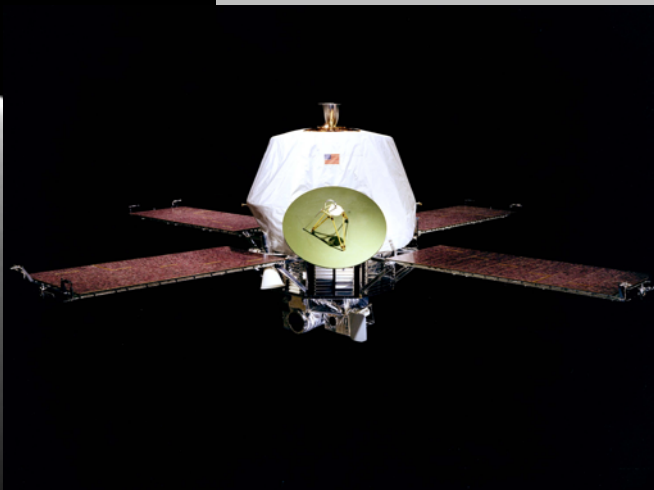


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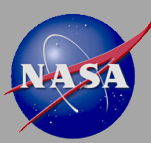
# Mariner 9: First to Orbit Another Planet



*Mars Exploration Program*

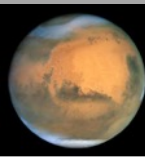


VALLES MARINERIS ON MARS (MARINER 9 / NASA)

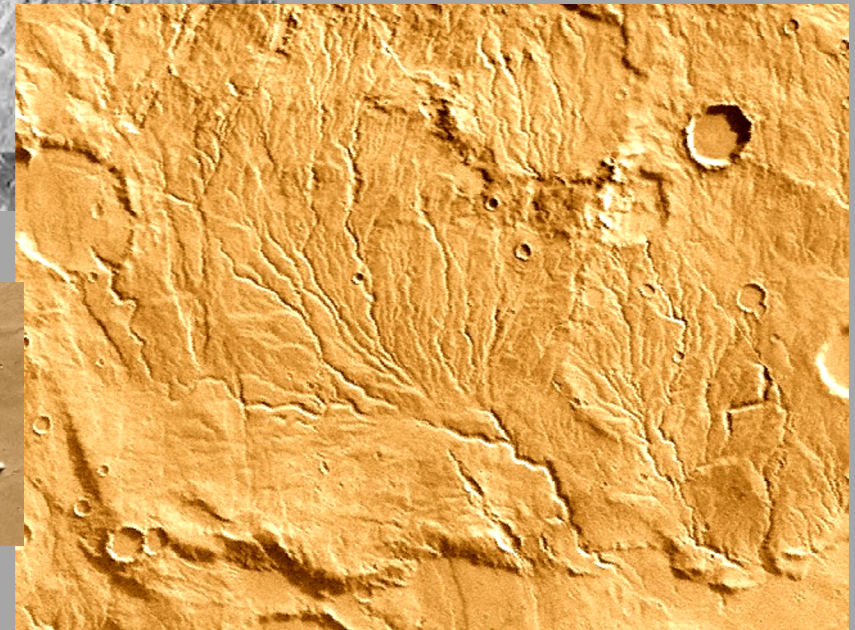
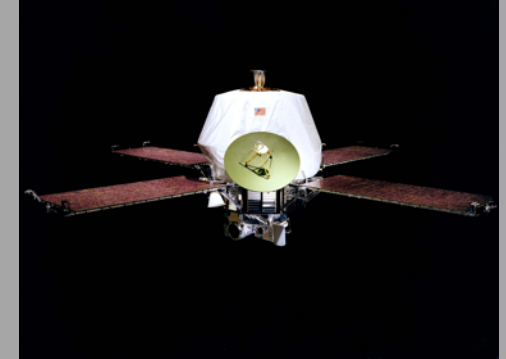
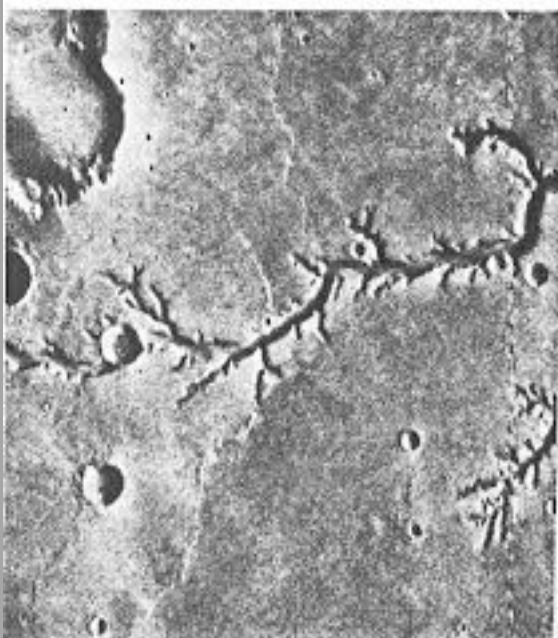


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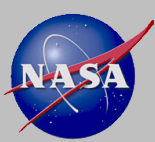
# Ancient Mars was Earth-like!



*Mars Exploration Program*

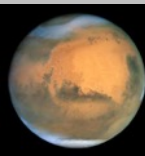




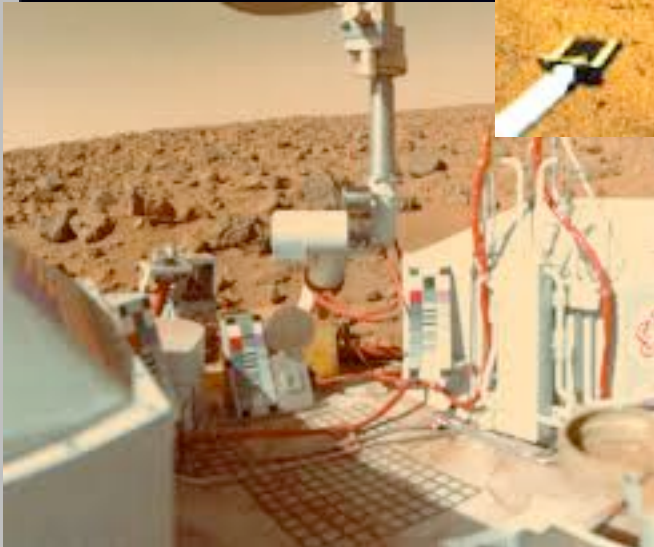
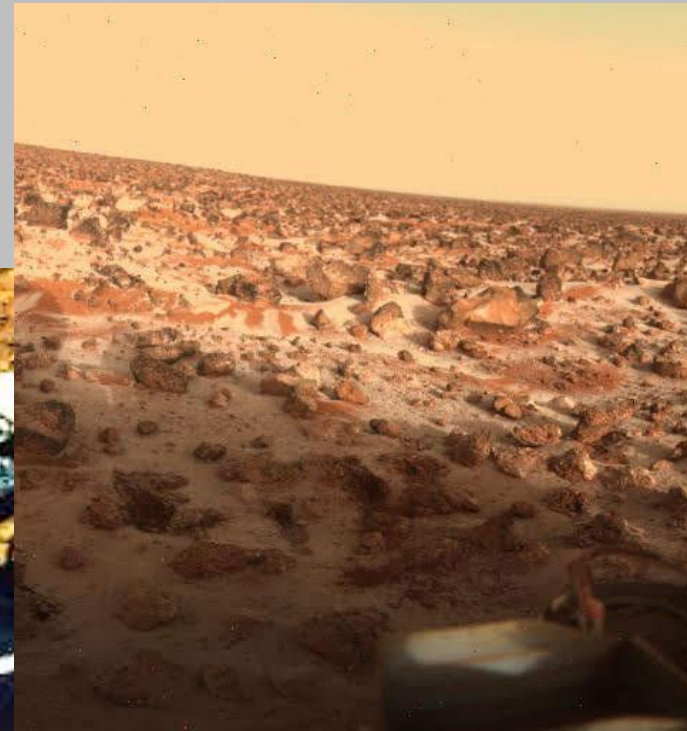
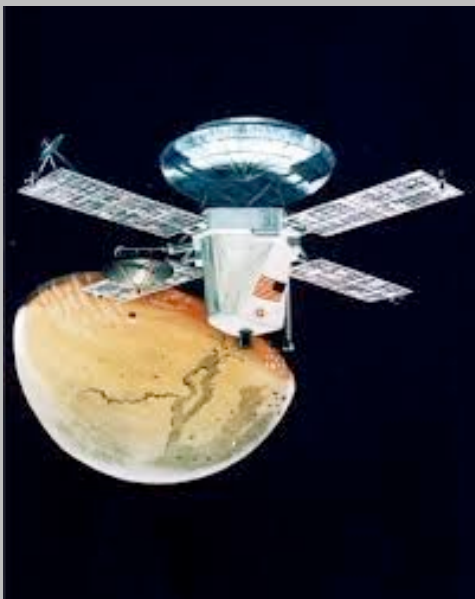


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# The Second Wave: Viking



*Mars Exploration Program*

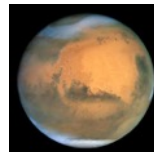


1976-1982

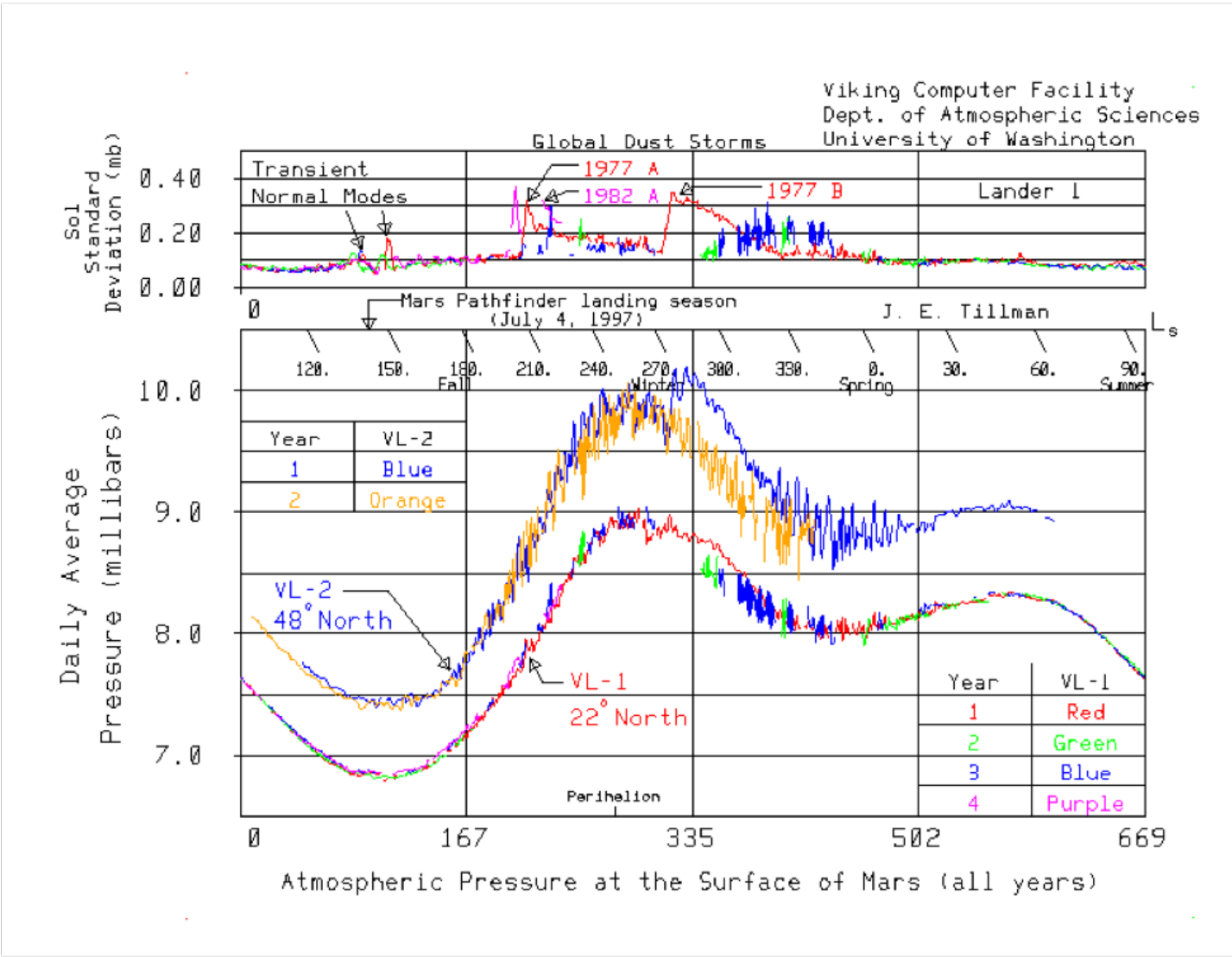




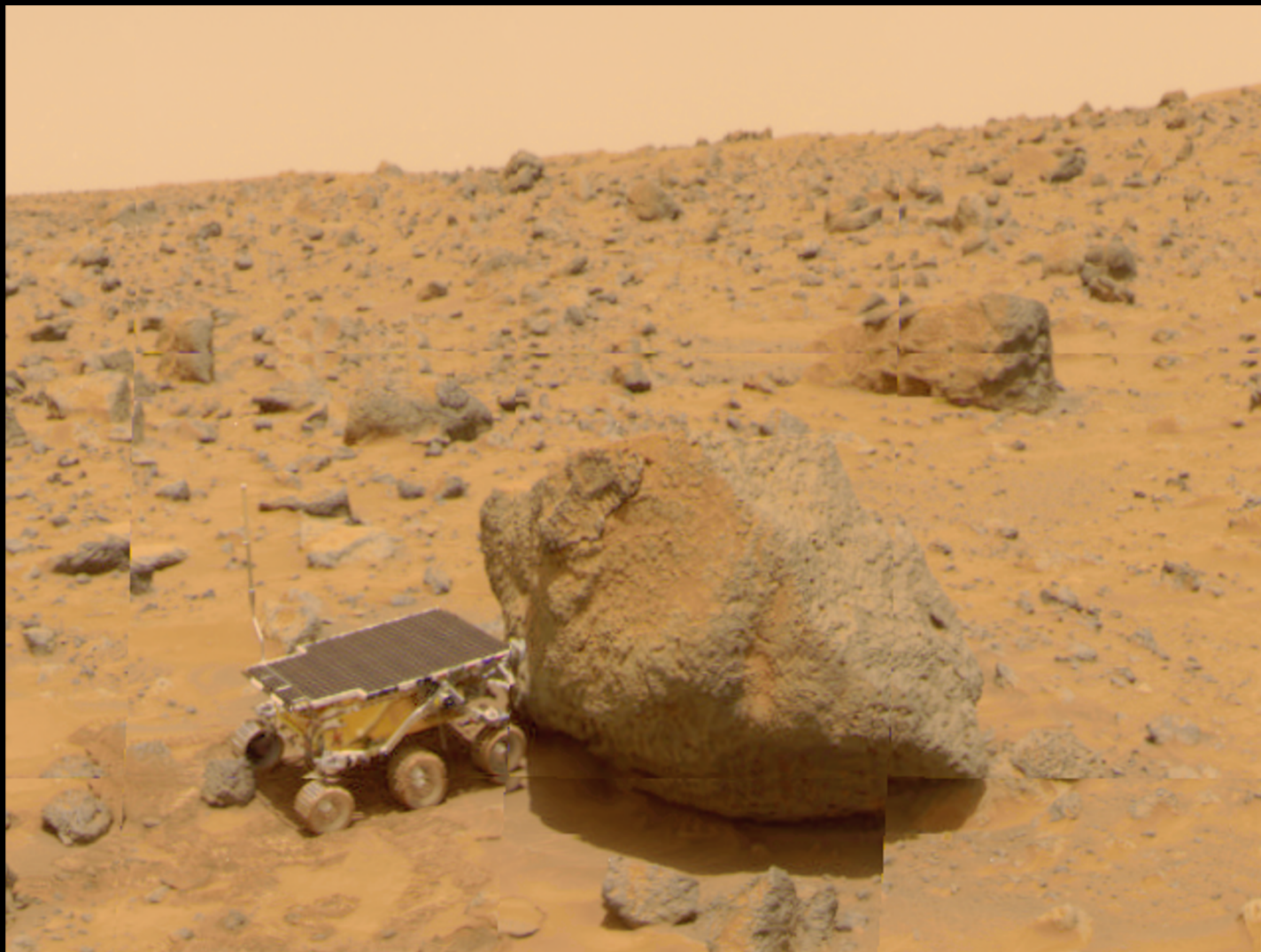
# Weather on Mars



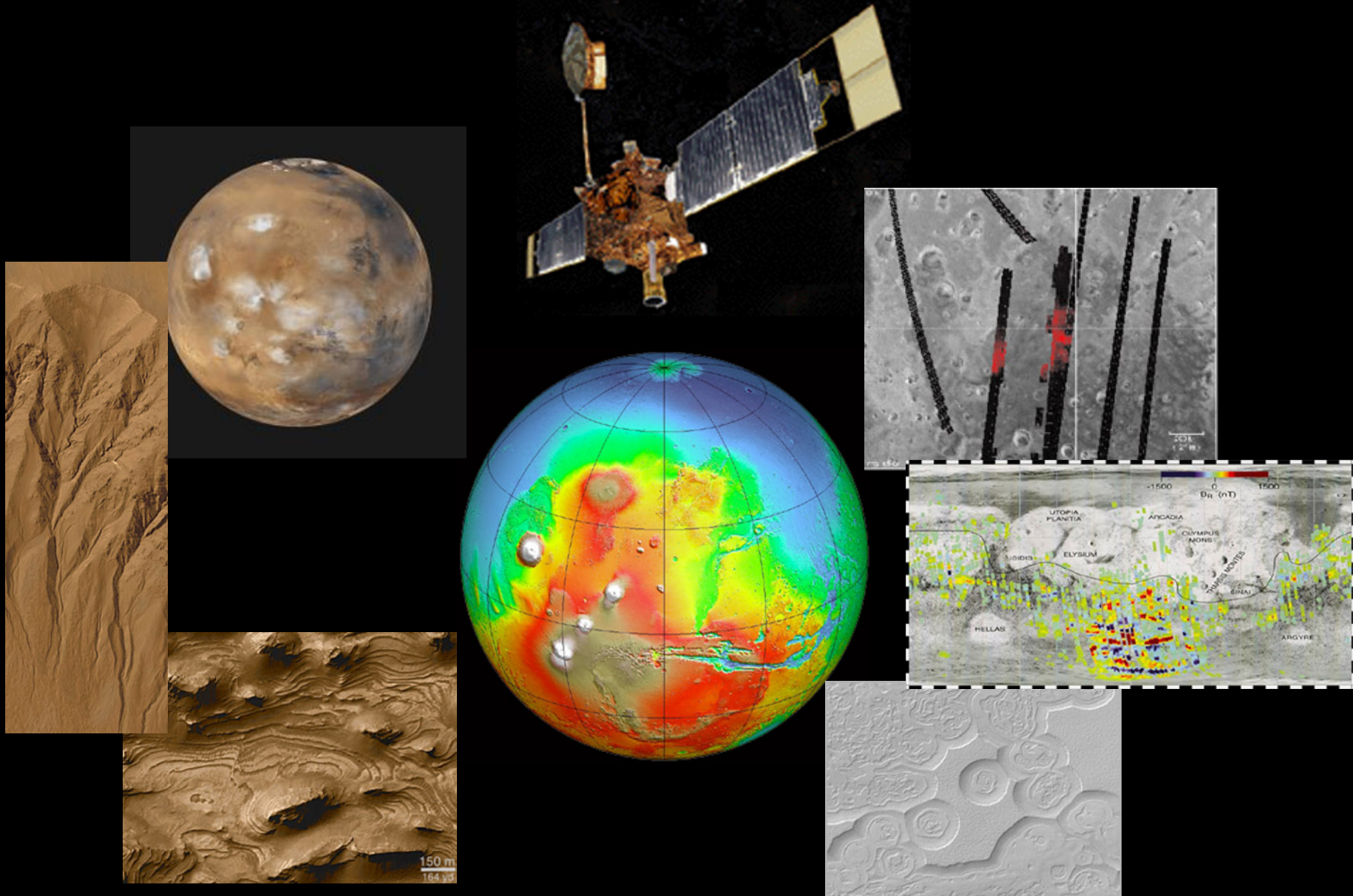
Mars Exploration Program



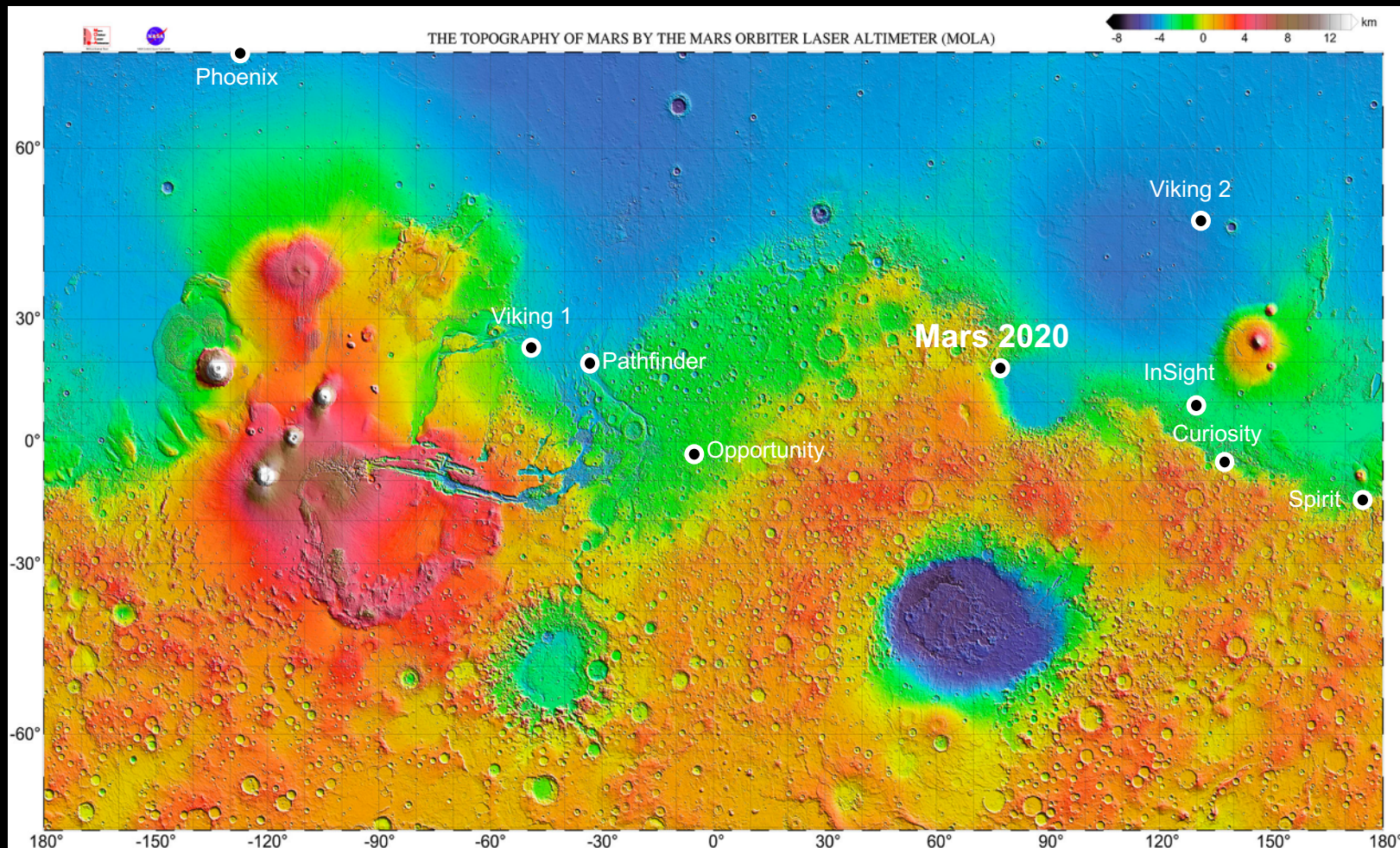
# *Mars Pathfinder: The Third Wave Begins*



# Mars Global Surveyor: A Science Catalyst for the Mars Exploration Program







# *MGS TES Climatology*

*Dust*

*T(K)*

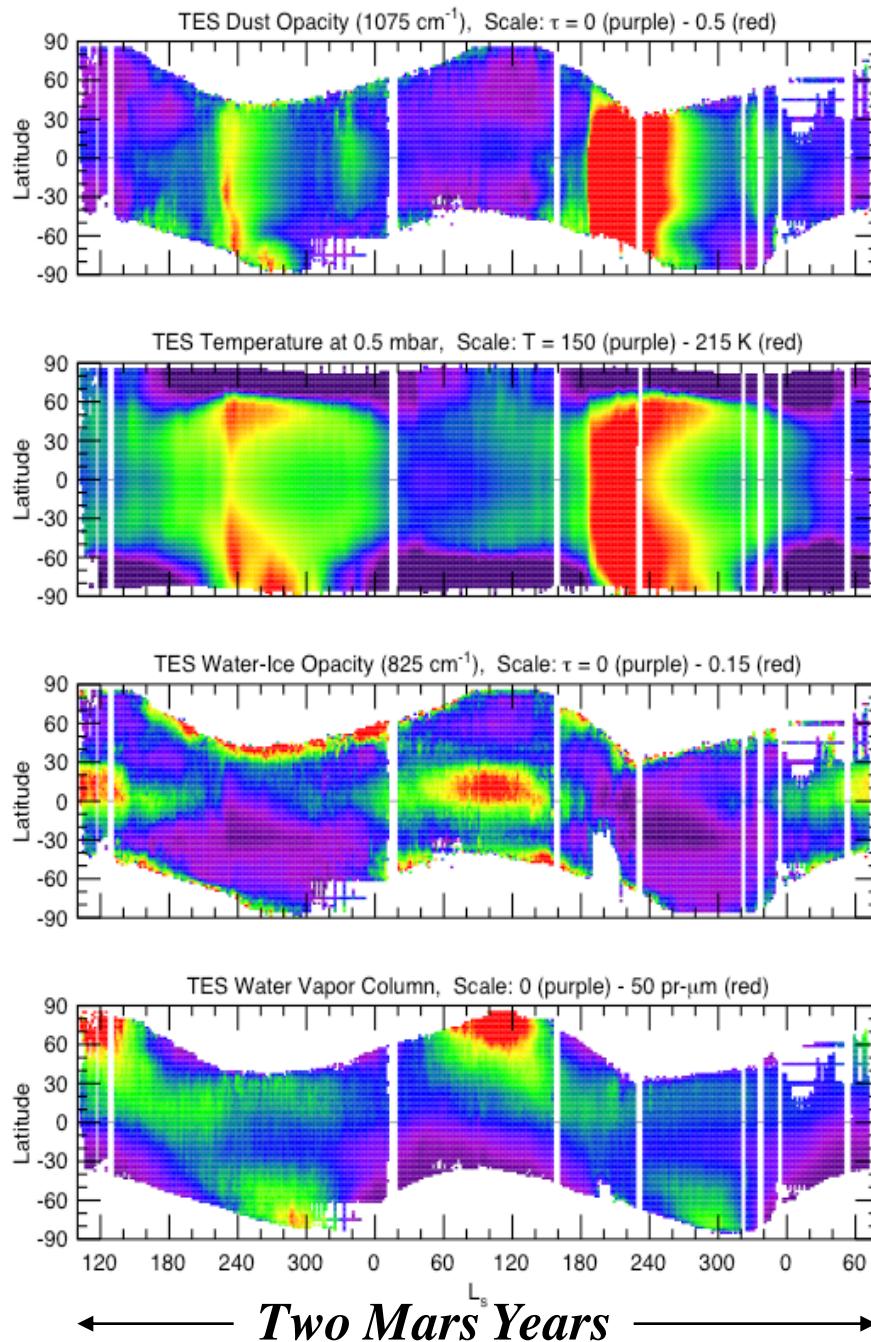
*ICE*

*Water  
Vapor*

**Zonally  
Averaged Fields  
during  
Two Mars Years**

*Courtesy of  
M. Smith  
TES Team*

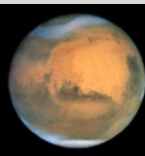
*(TES PI: P. Christensen)  
NASA / JPL / ASU / GSFC*



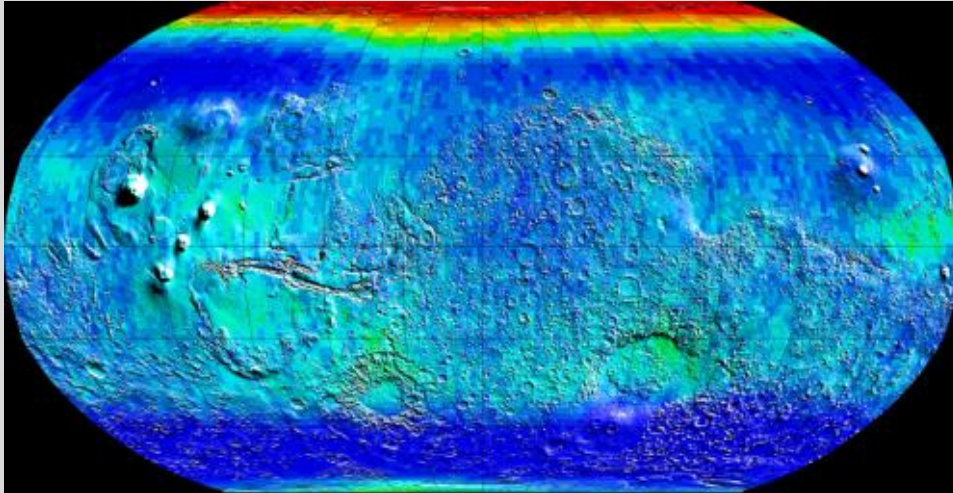




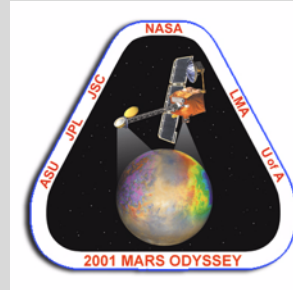
# Probing the Subsurface



Mars Exploration Program

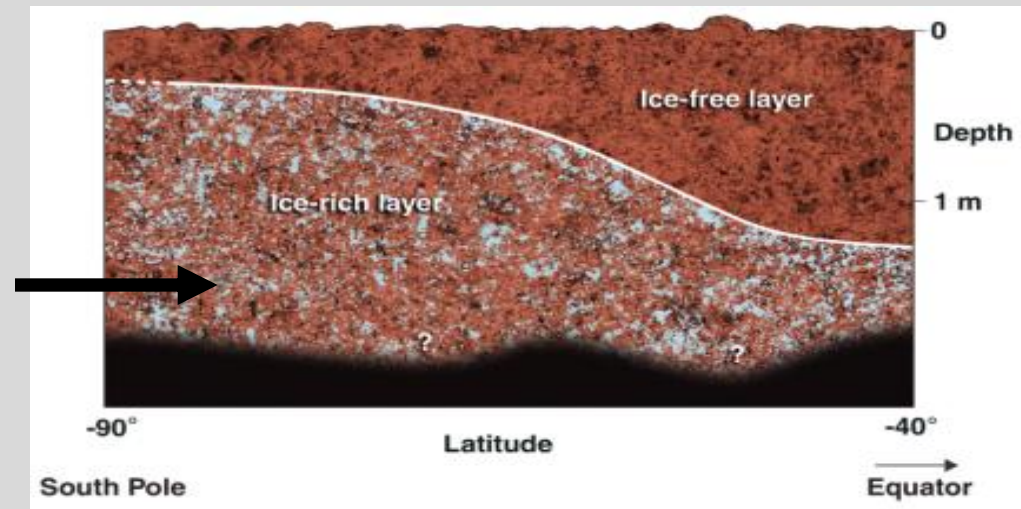


**Hydrogen (Ice) Map**  
*2001 Mars Odyssey*  
*GRS-Neutron*  
*Spectrometer*  
*& HEND*



*NASA / JPL / University of Arizona*  
*Los Alamos National Laboratory*

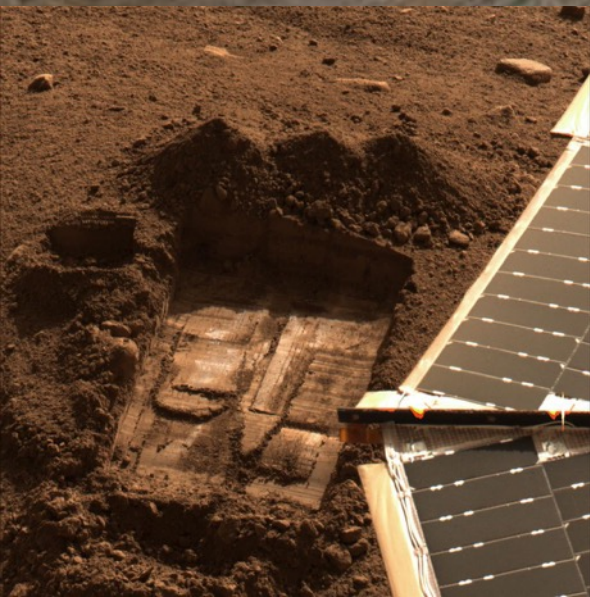
**How Deep is this Layer?**  
**Is it in Equilibrium with**  
**Today's Climate?**  
**Is it the Top of the Ancient**  
**Water Reservoir?**





# Phoenix *Scout* Mission 2008

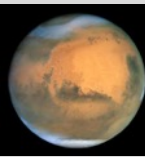
Landing 65° – 75° North



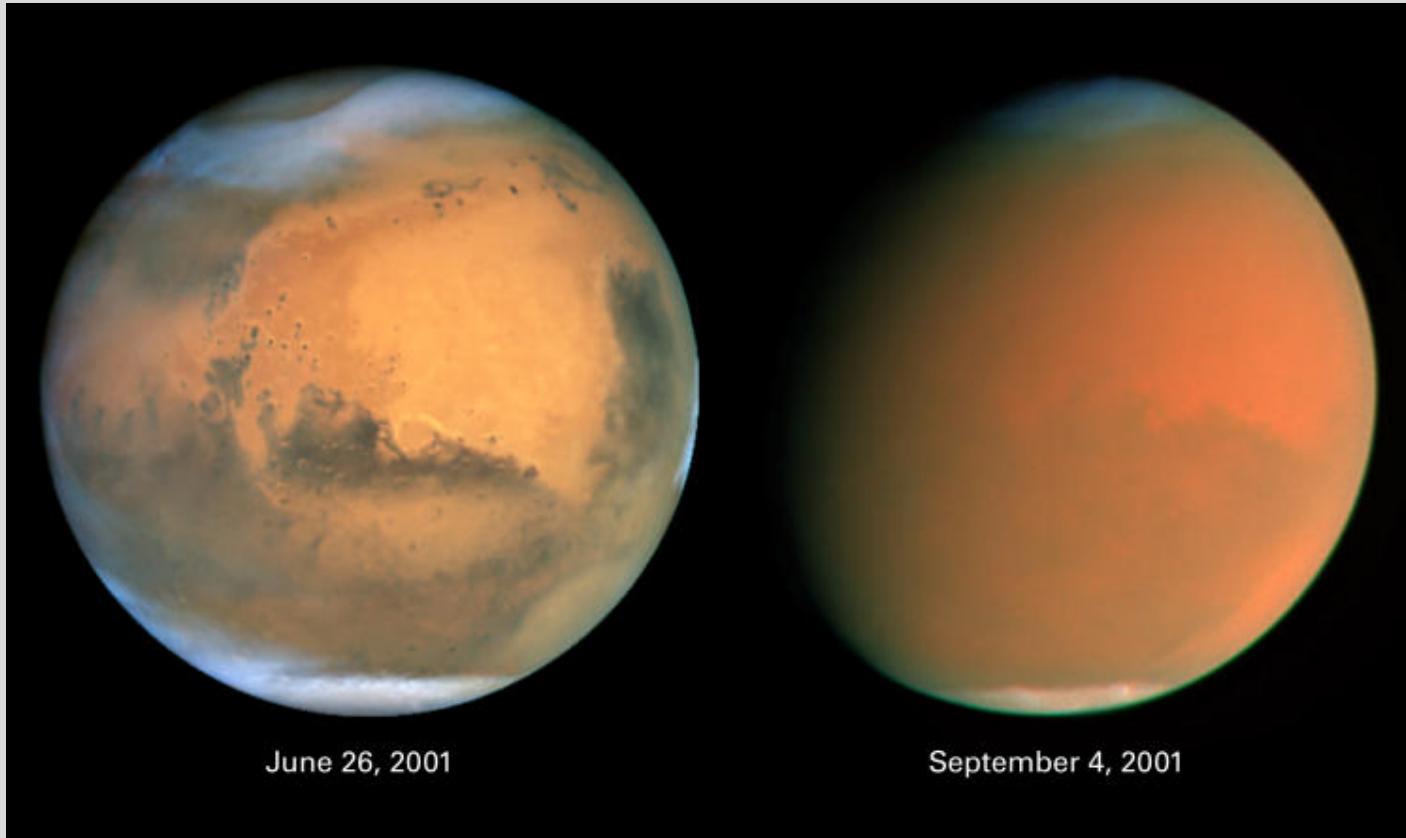


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# HST View in 2001



*Mars Exploration Program*

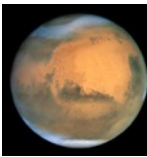


**CREDIT: NASA / STScI / AURA / J. Bell & M. Wolff**





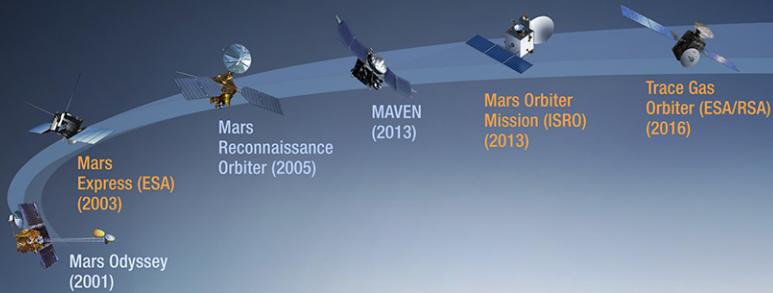
# Modern Mars Missions



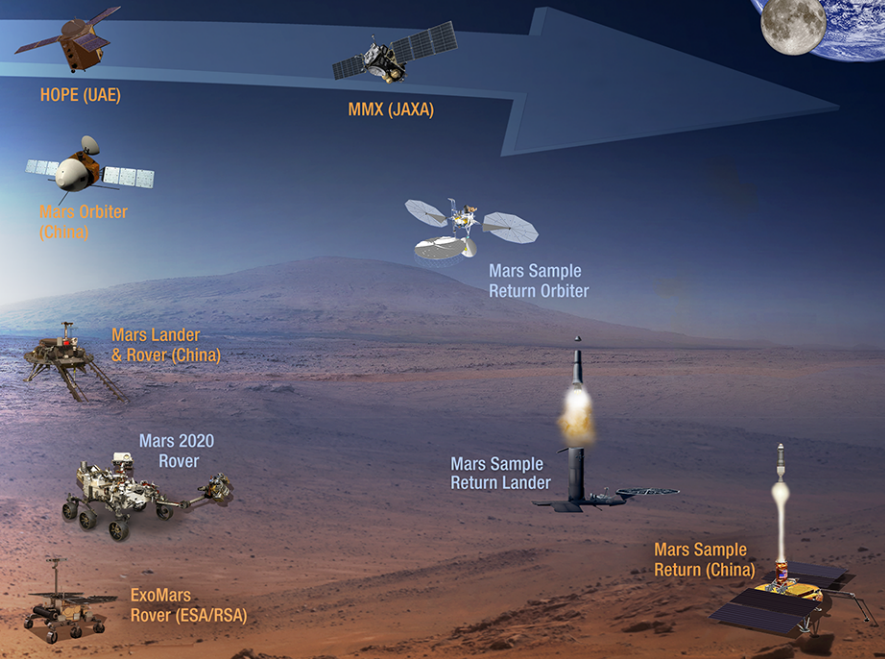
*Mars Exploration Program*

## MARS MISSIONS

### OPERATIONAL 2001–2019



### 2020 AND BEYOND



Follow the Water

Explore Habitability

Seek Signs of Life

Prepare for Future Human Explorers

U.S. Missions

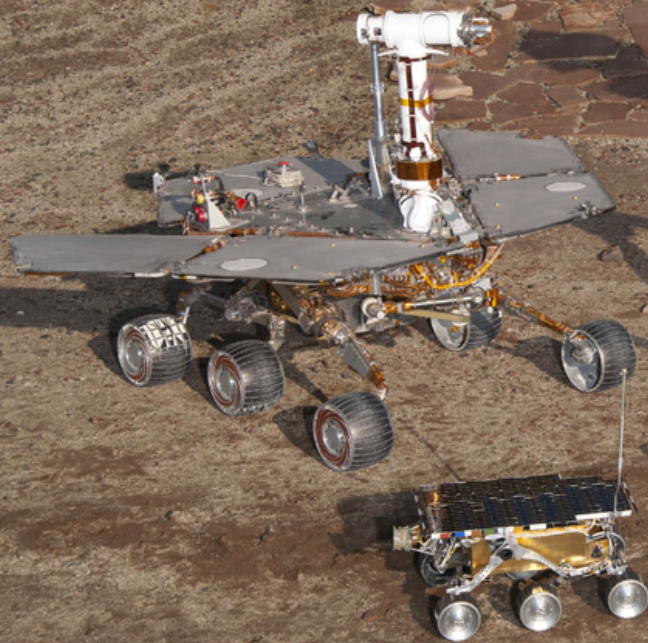
non-U.S. Missions

Future Mars Sample Return Orbiters and Landers are pre-decisional and are shown for planning and discussion only.

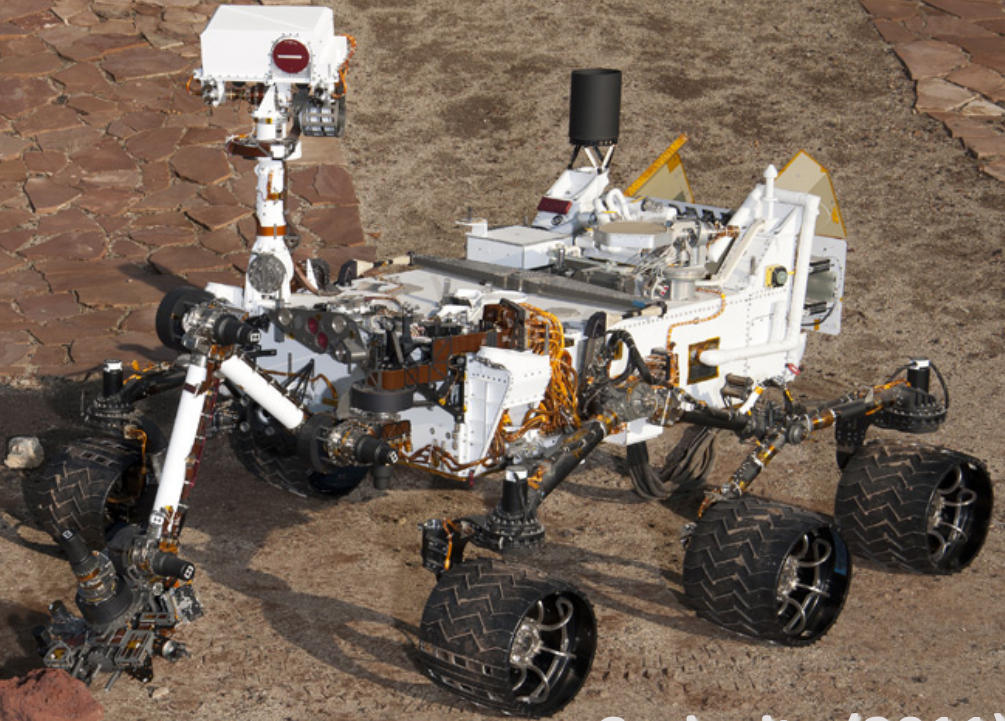


10.5 kg → 174 kg → 900 kg

Spirit/Opportunity  
(2004)



Curiosity (2011)



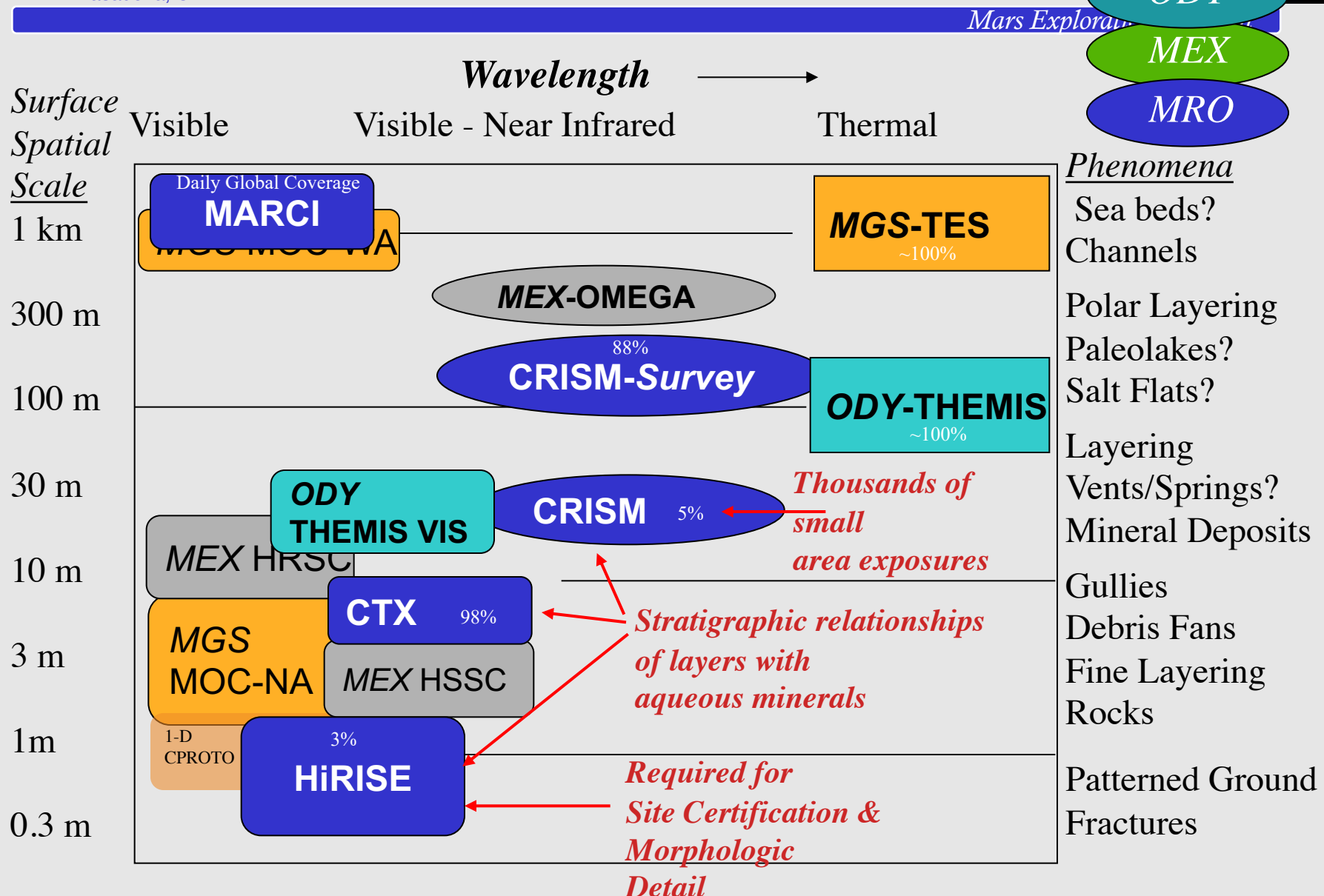
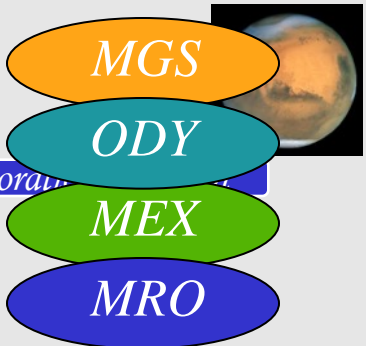
Pathfinder /  
Sojourner (1997)







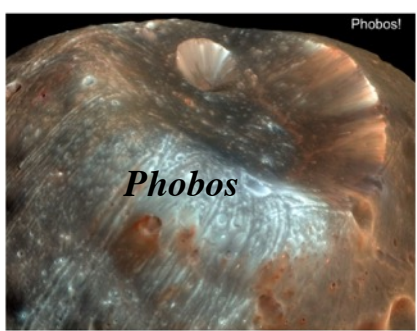
# Gains in Resolution



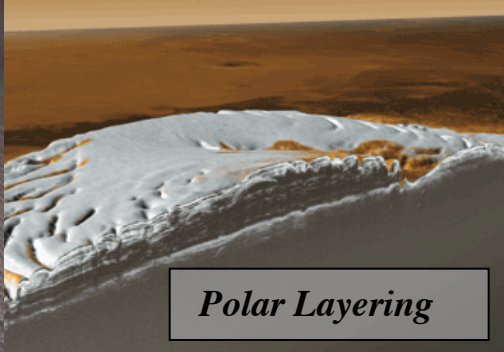




*Diverse Mineralogy*



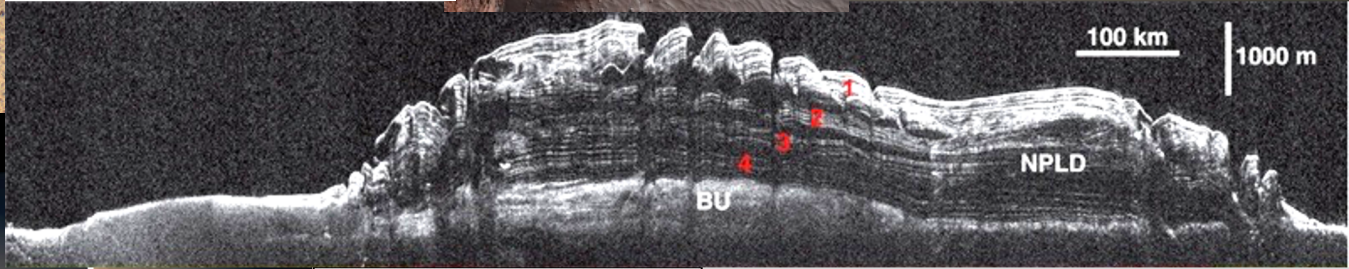
*Phobos*



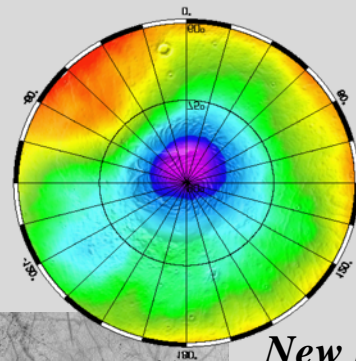
*Polar Layering*



*Dust Storms*



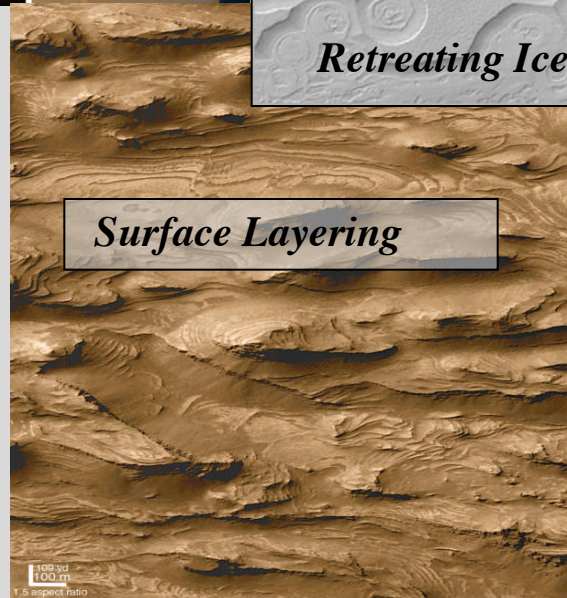
*Retreating Ice*



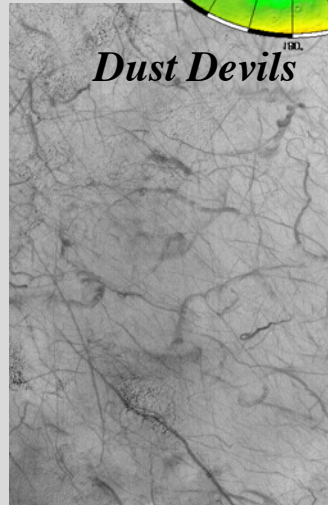
*Subsurface Ice*



*Surface Change Today*



*Surface Layering*



*Dust Devils*



*New Ice Exposed*

Site 3: L<sub>s</sub> 151°

October 14, 2019

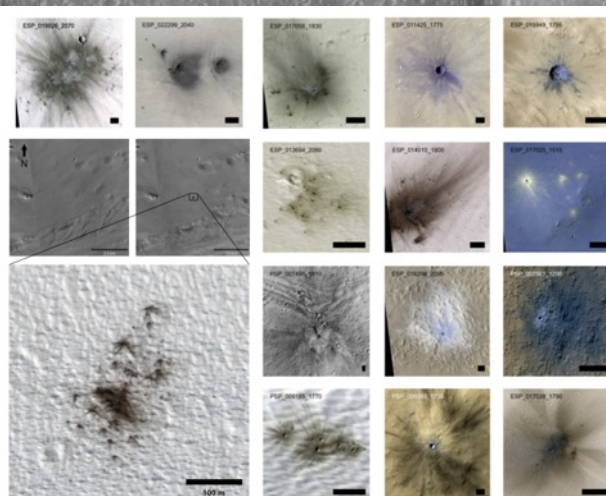
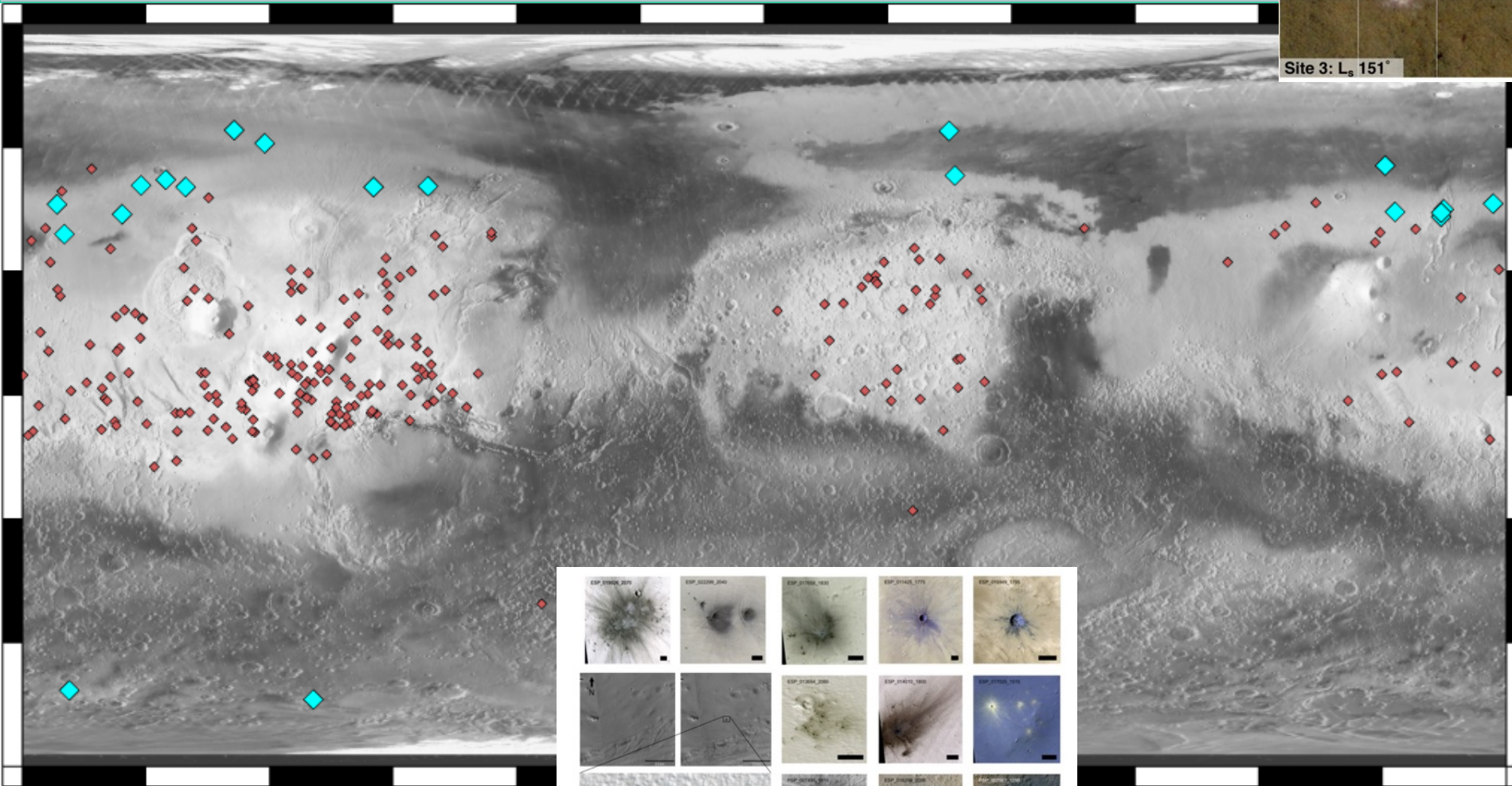
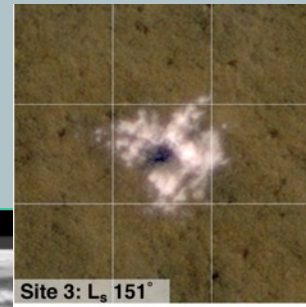
RZ-20



# Locations of New Impact Craters

*Blue-filled Diamonds Are Those Exposing Ice*

*HiRISE / USGS / U. Arizona / JPL-Caltech / NASA*

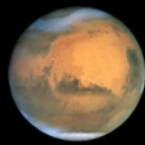




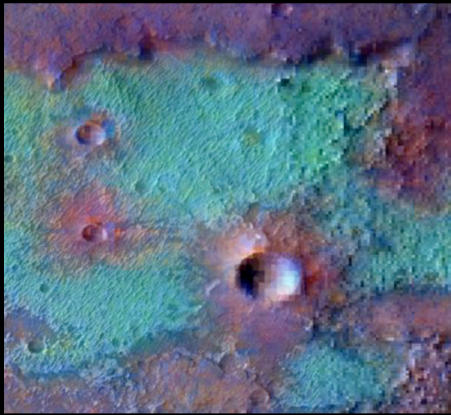
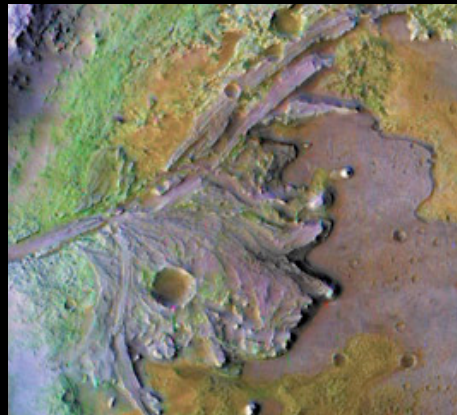
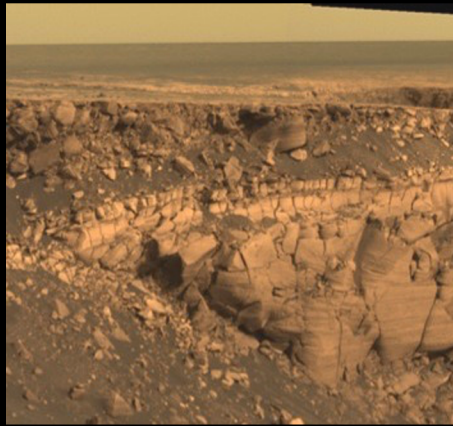
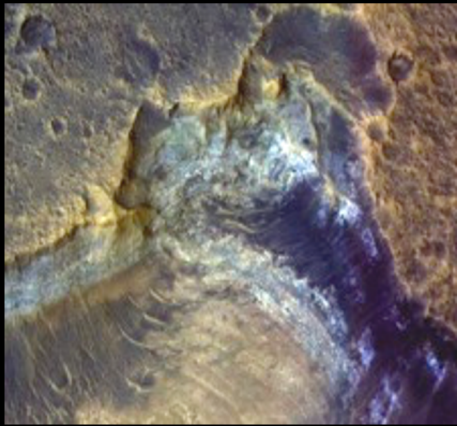


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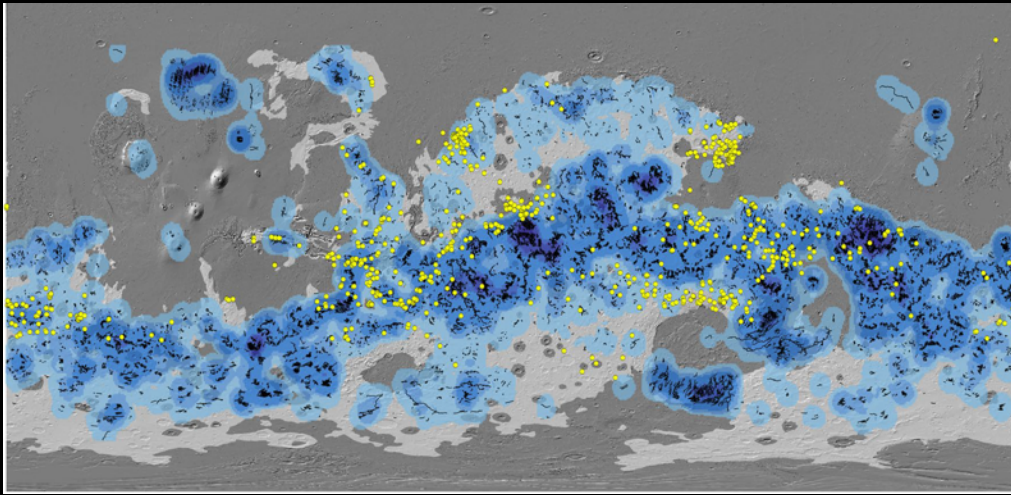
# Diversity of Martian Environments



Mars Exploration Program



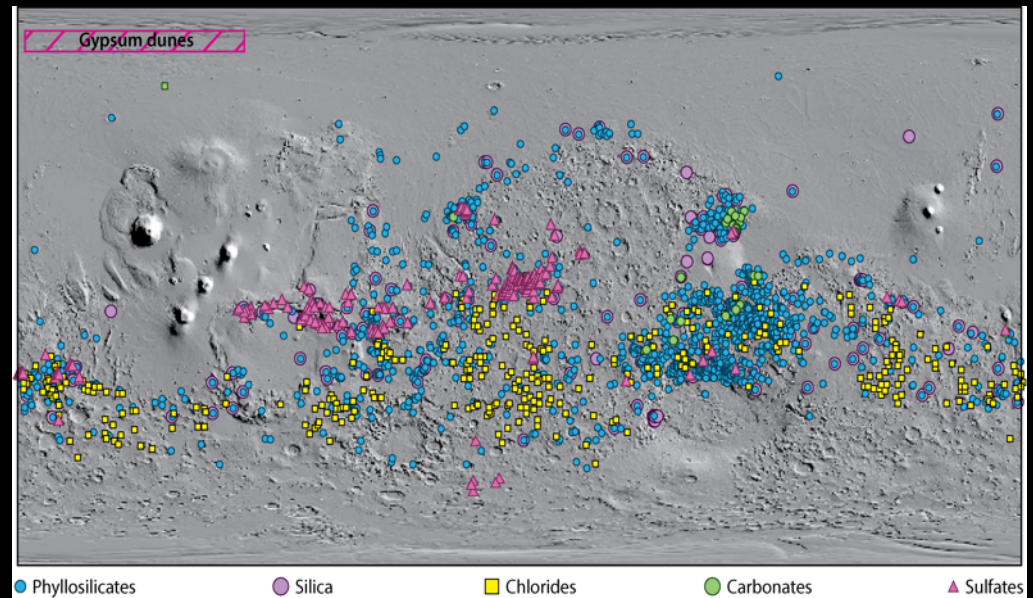




*MRO CRISM: Clays  
(yellow) formed in  
warm, wet conditions  
near dense valley  
networks (blue)*

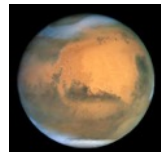
Observed Outcrops of  
Minerals Formed in Liquid  
Water

Ehlmann & Edwards (2014)

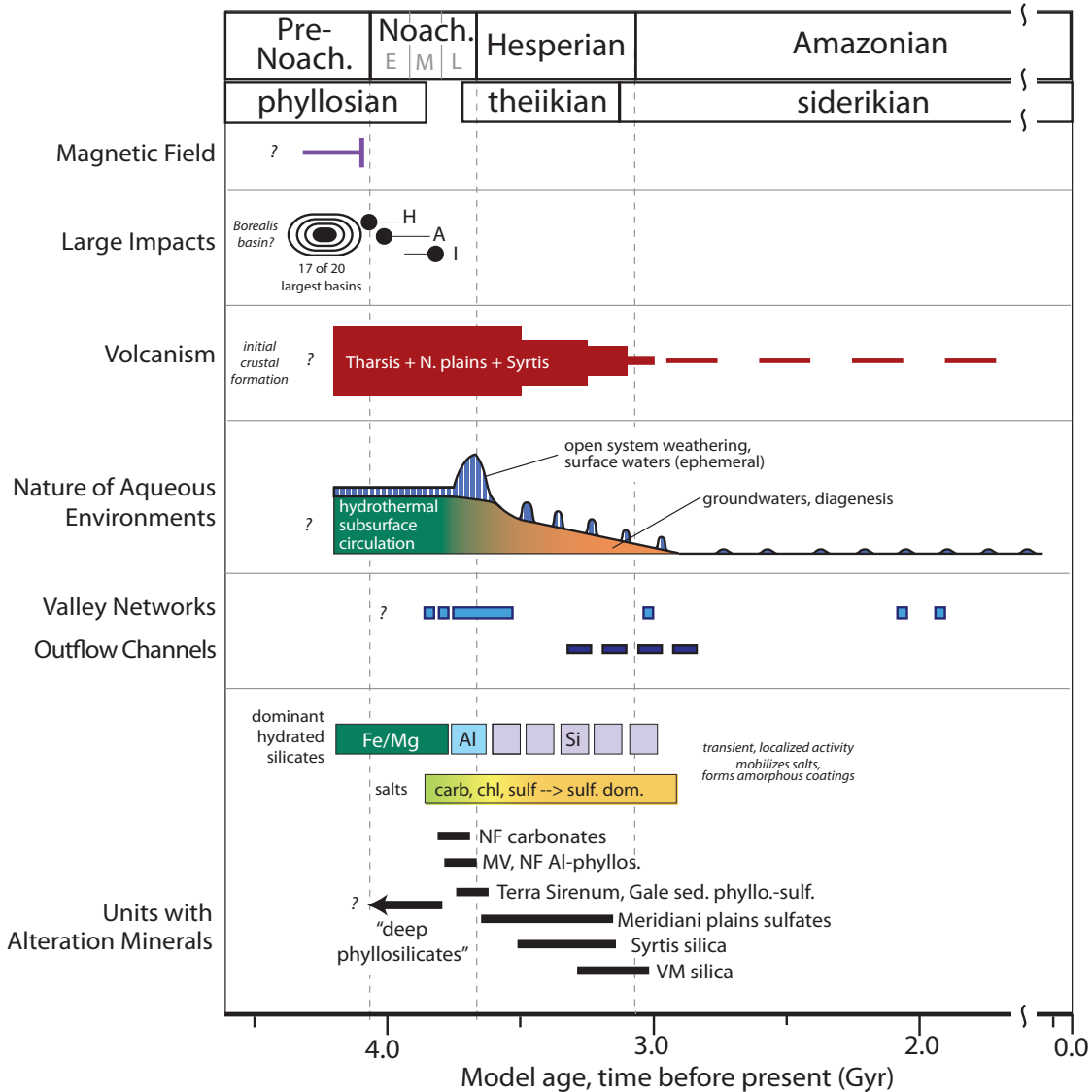




# Mars: Changing with Time

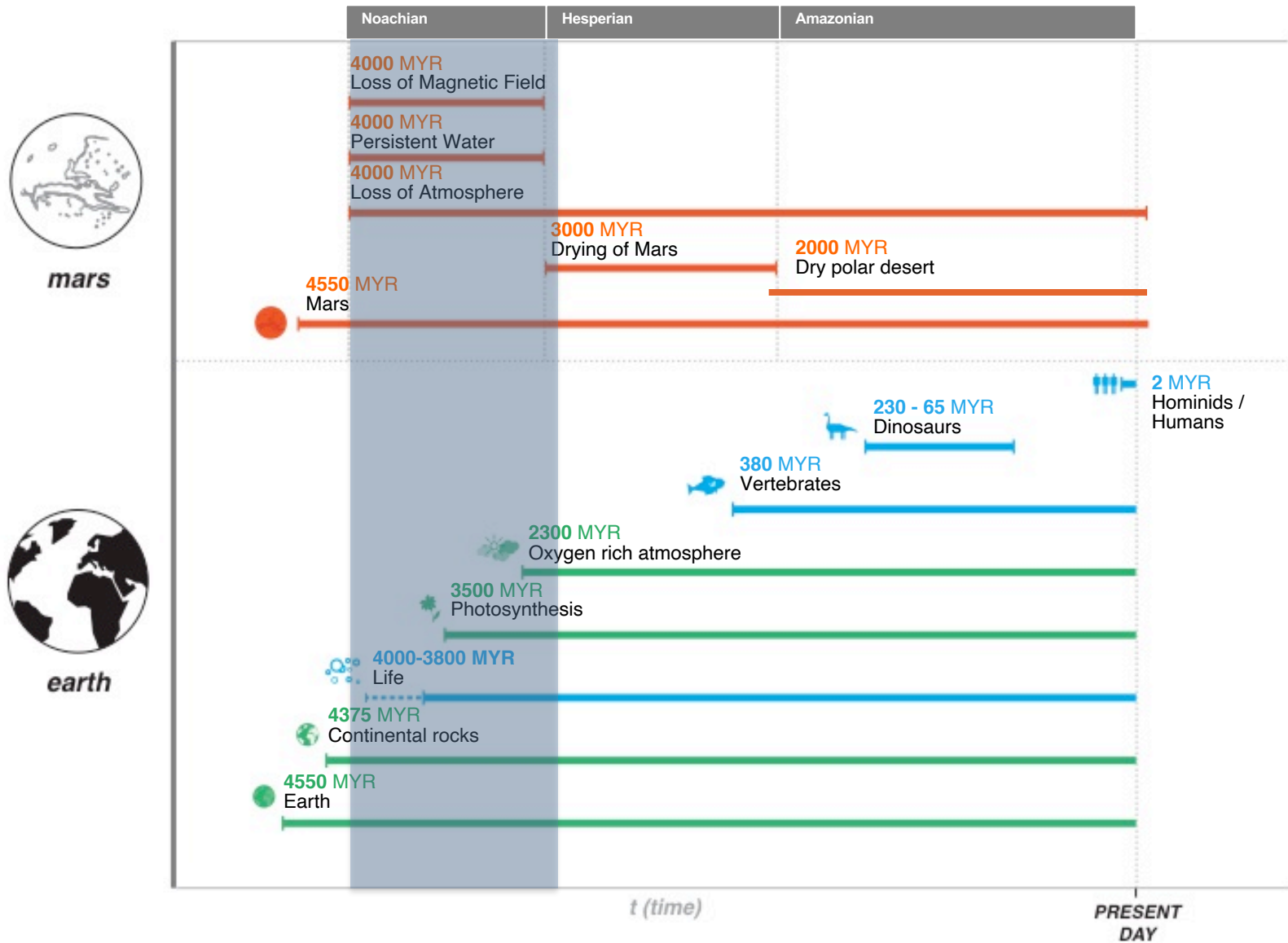


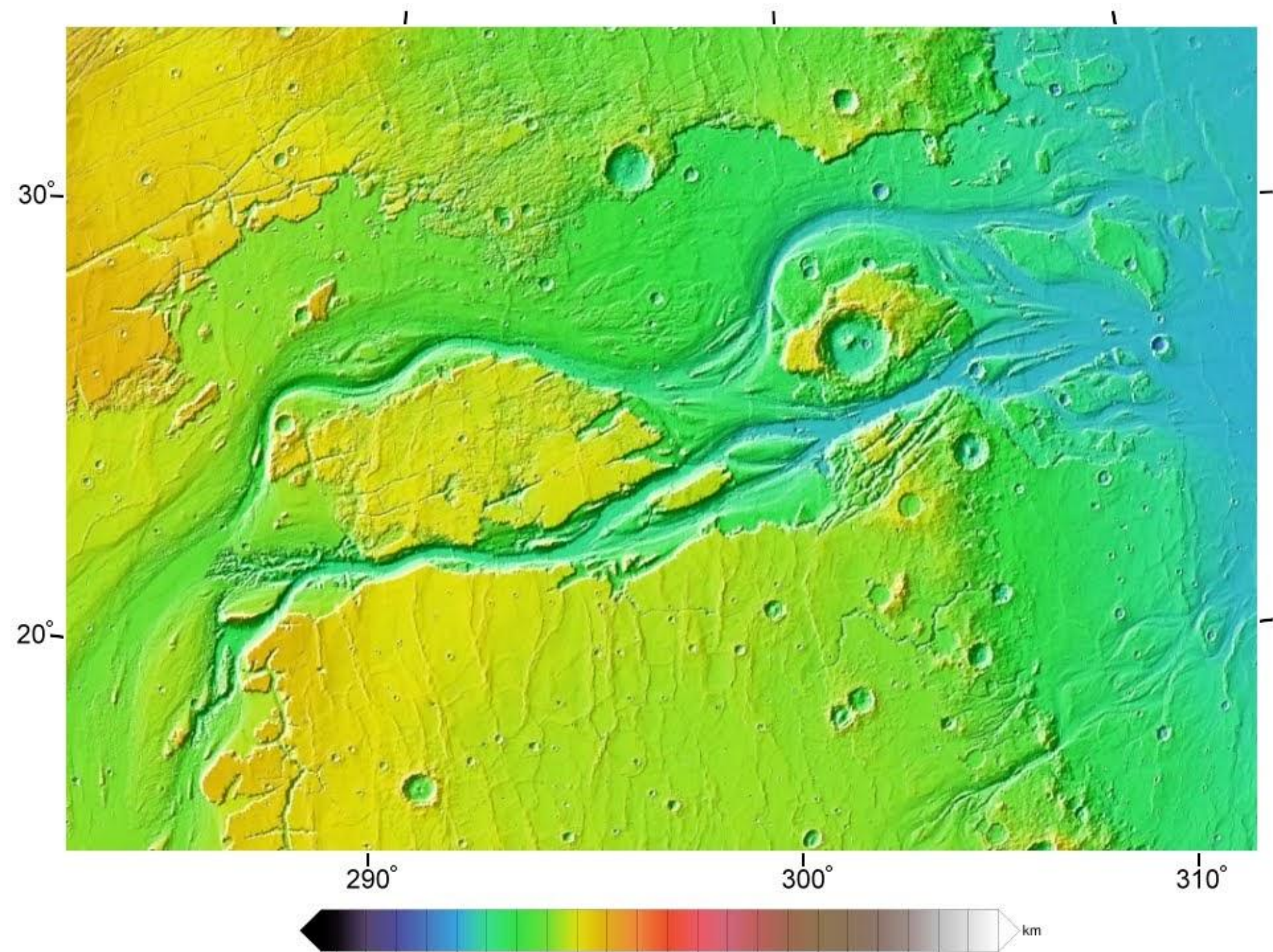
Mars Exploration Program





# Earth + Mars Life Cycle Comparison



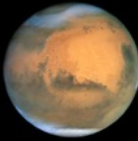






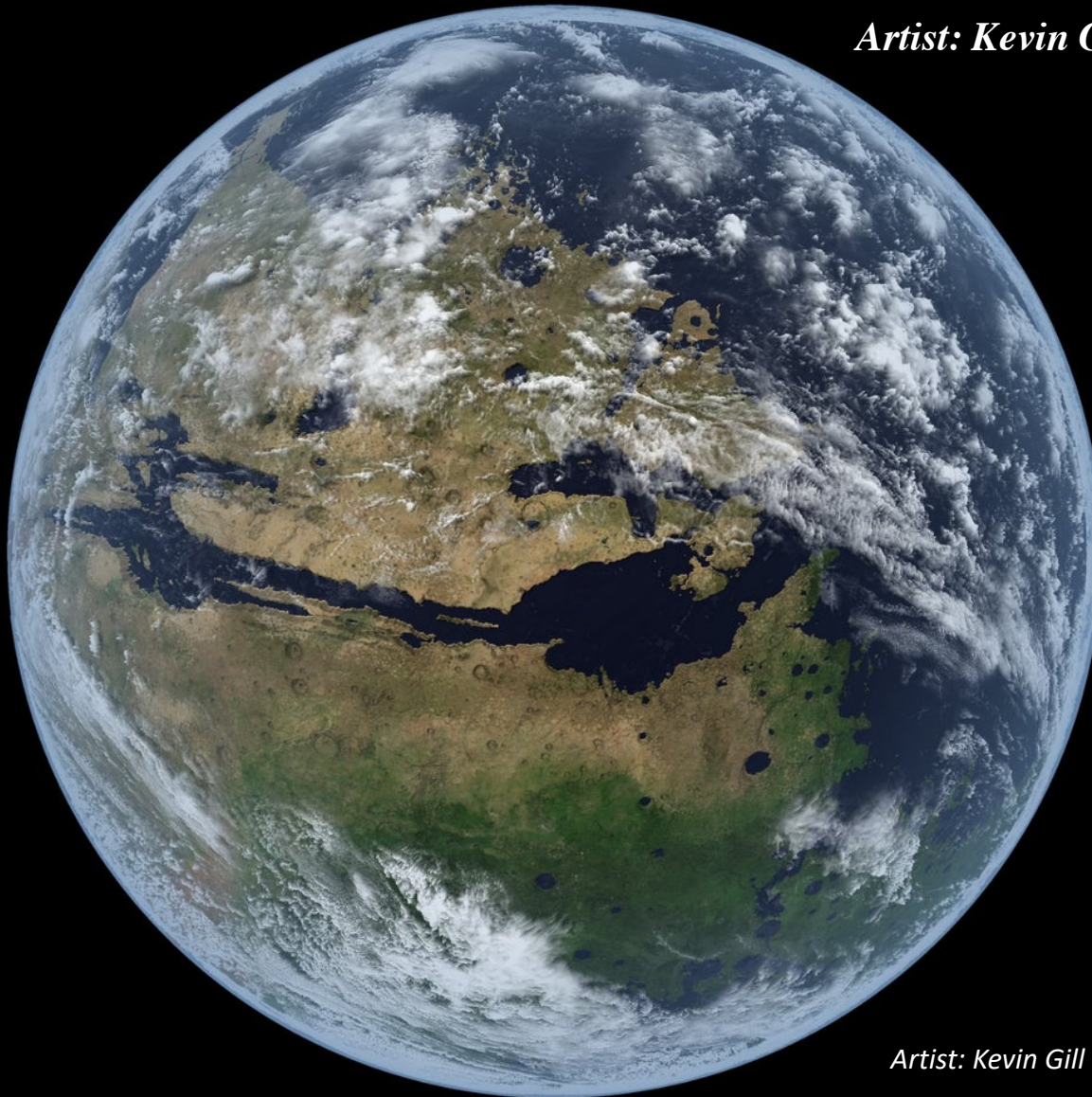
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# Ancient Mars?



*Mars Exploration Program*

*Artist: Kevin Gill*



*Artist: Kevin Gill*



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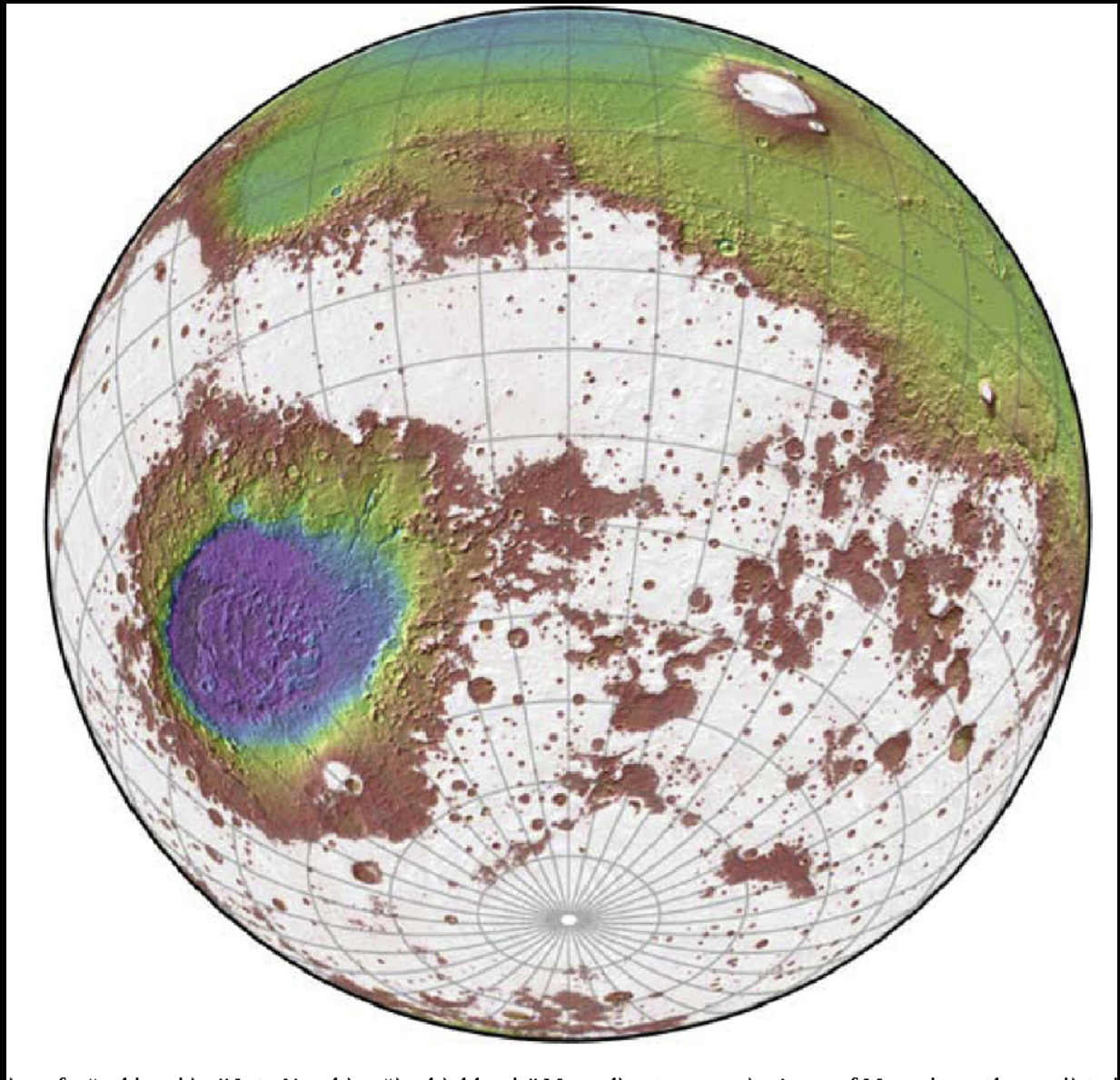
# Ancient Mars?



*Mars Exploration Program*

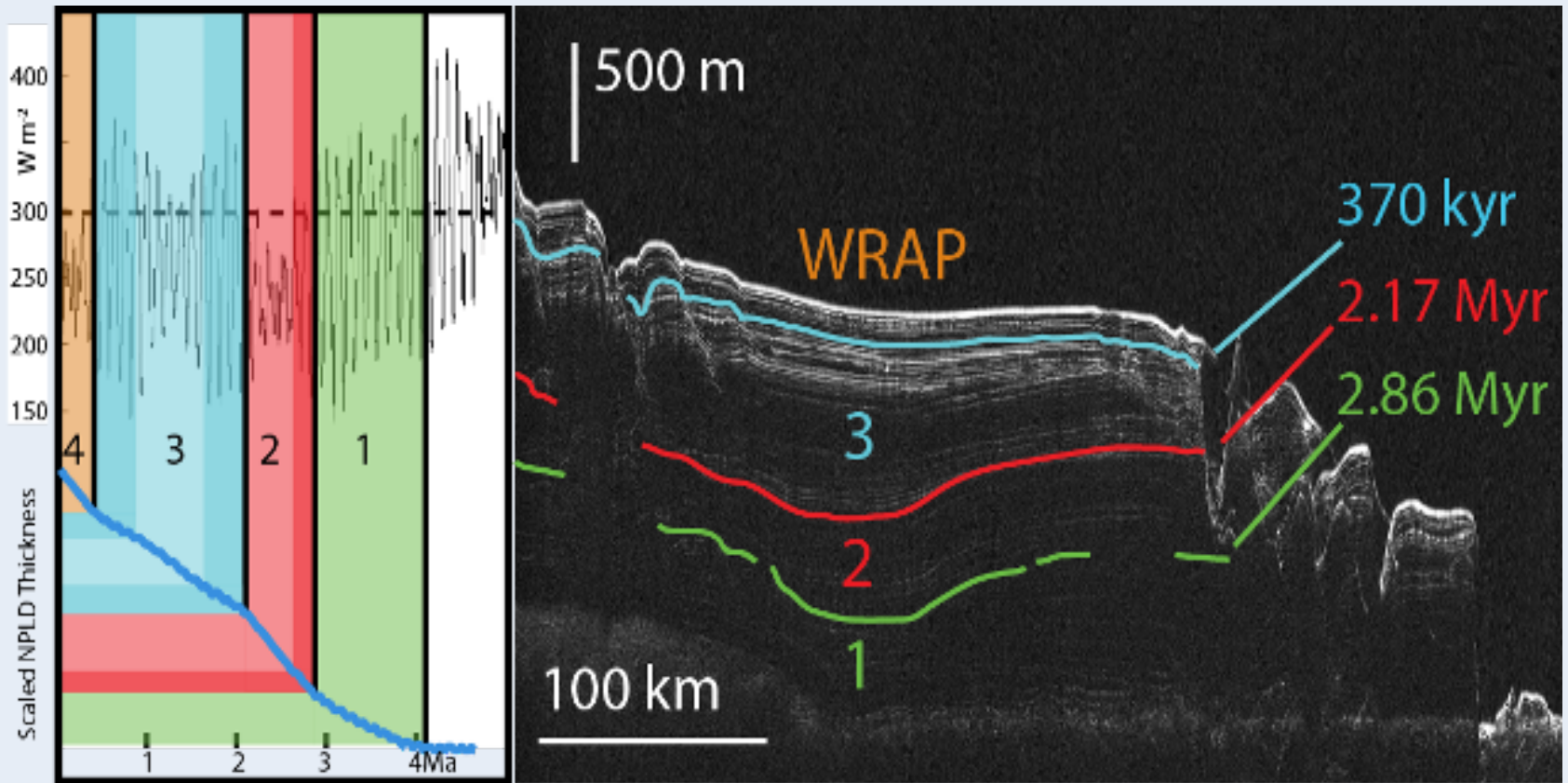
## Icy Highlands Model

*Wordsworth et al.,  
2013; Head and  
Marchant, 2014*





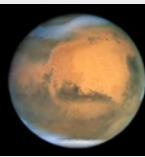
# Martian Ice Age Record?



Correspondence of insolation history and modeled thickness of NPLD by *Levrard et al.* [2007] (left panel) with layering sequences bounded by subsurface unconformities mapped with SHARAD [Smith et al., in review].



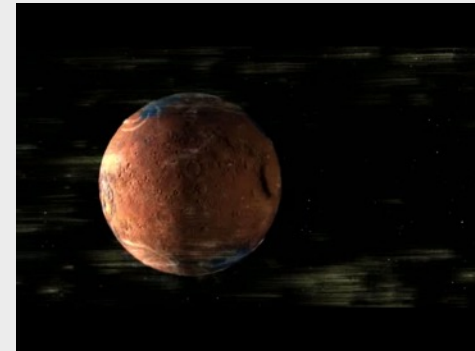
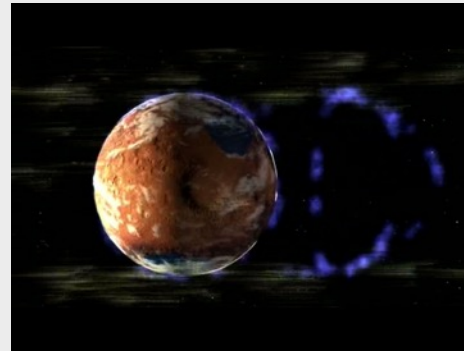
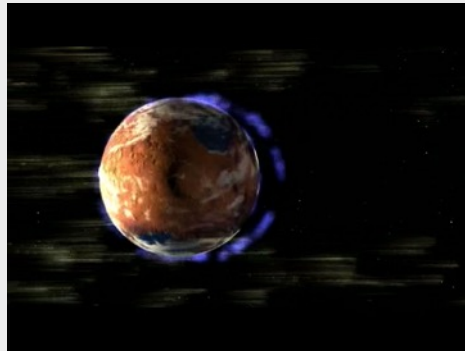
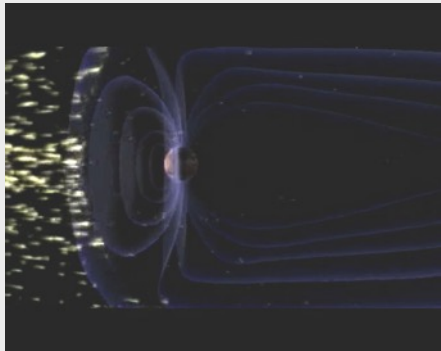
# MAVEN: *Loss of an Atmosphere*



*Mars Exploration Program*

MAVEN is addressing questions about the history of Martian volatiles and atmosphere and help us to understand the nature of planetary habitability.

- Determine the structure and composition of the Martian upper atmosphere today
- Determine rates of loss of gas to space today ( $> 100$  gms/sec)
- Measure properties and processes that will allow us to determine the integrated loss to space through time (effects of solar storms/UV)



*Turn-off of the Martian magnetic field allowed turn-on of solar-EUV and solar-wind stripping of the atmosphere approximately 3.7 billion years ago, resulting in the present thin, cold atmosphere.*

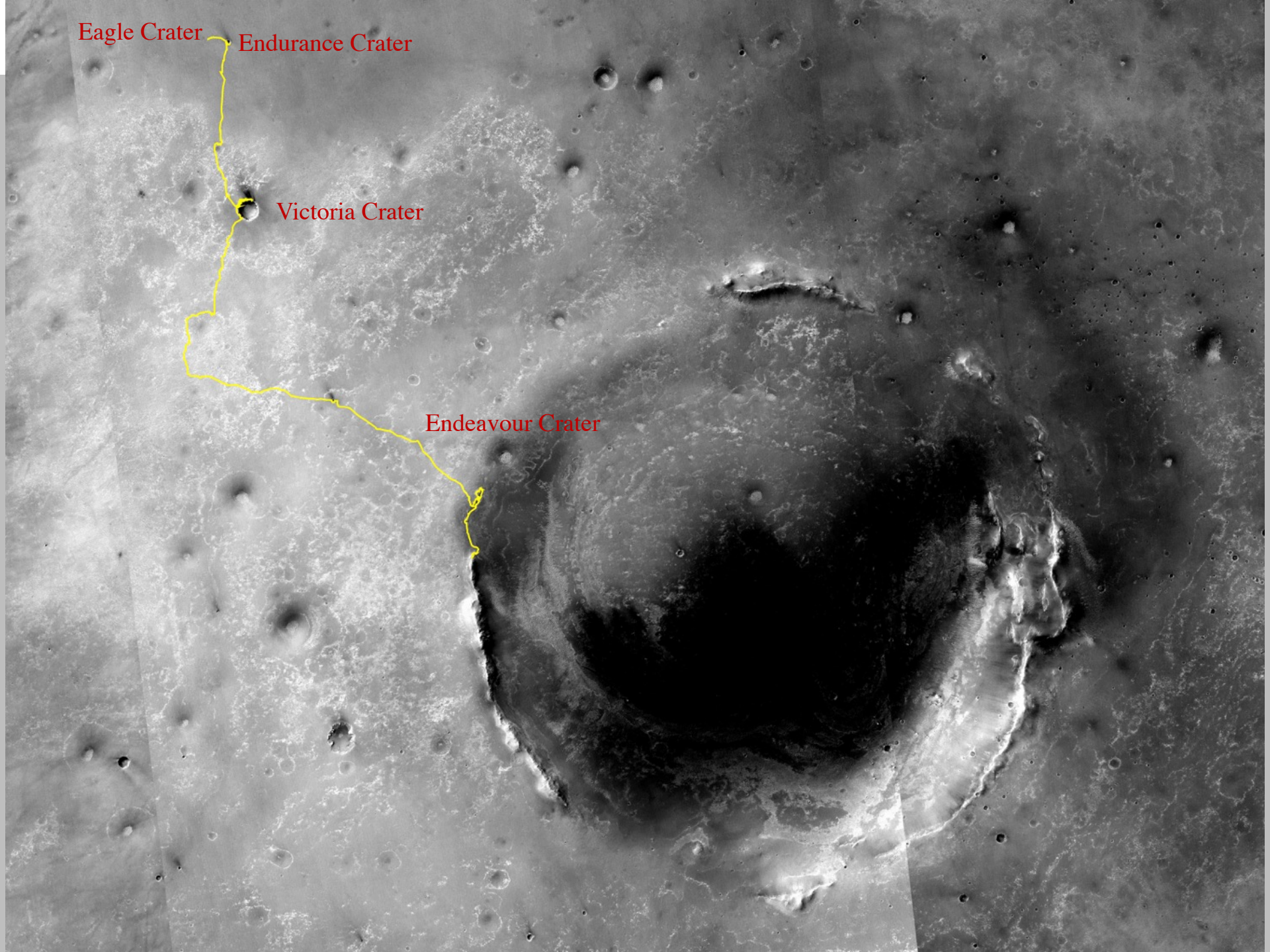


Eagle Crater

Endurance Crater

Victoria Crater

Endeavour Crater





## Burns Cliff Endurance Crater

Ancient Streams

Ancient  
Dunes

Ancient Groundwater

1 meter

Eagle Crater

Landing  
January 25  
2004

End of 90 sol  
warranty  
2005

Endurance Crater

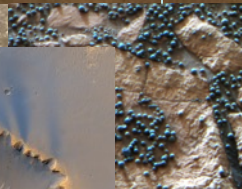
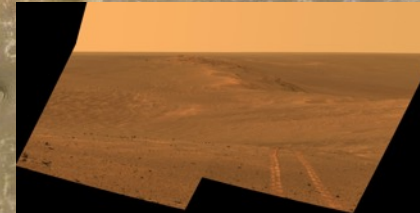
Victoria Crater

Endeavour Crater

Purgatory

Last Communication  
June 10 2018

Sol 5111







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# *Opportunity's* Final Resting Place



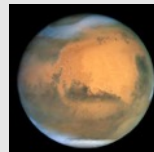
MRO HiRISE / U. Arizona / JPL / NASA



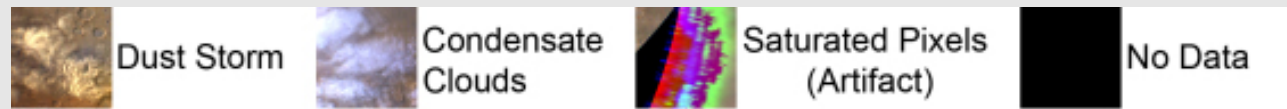


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# Full MARCI Global Map



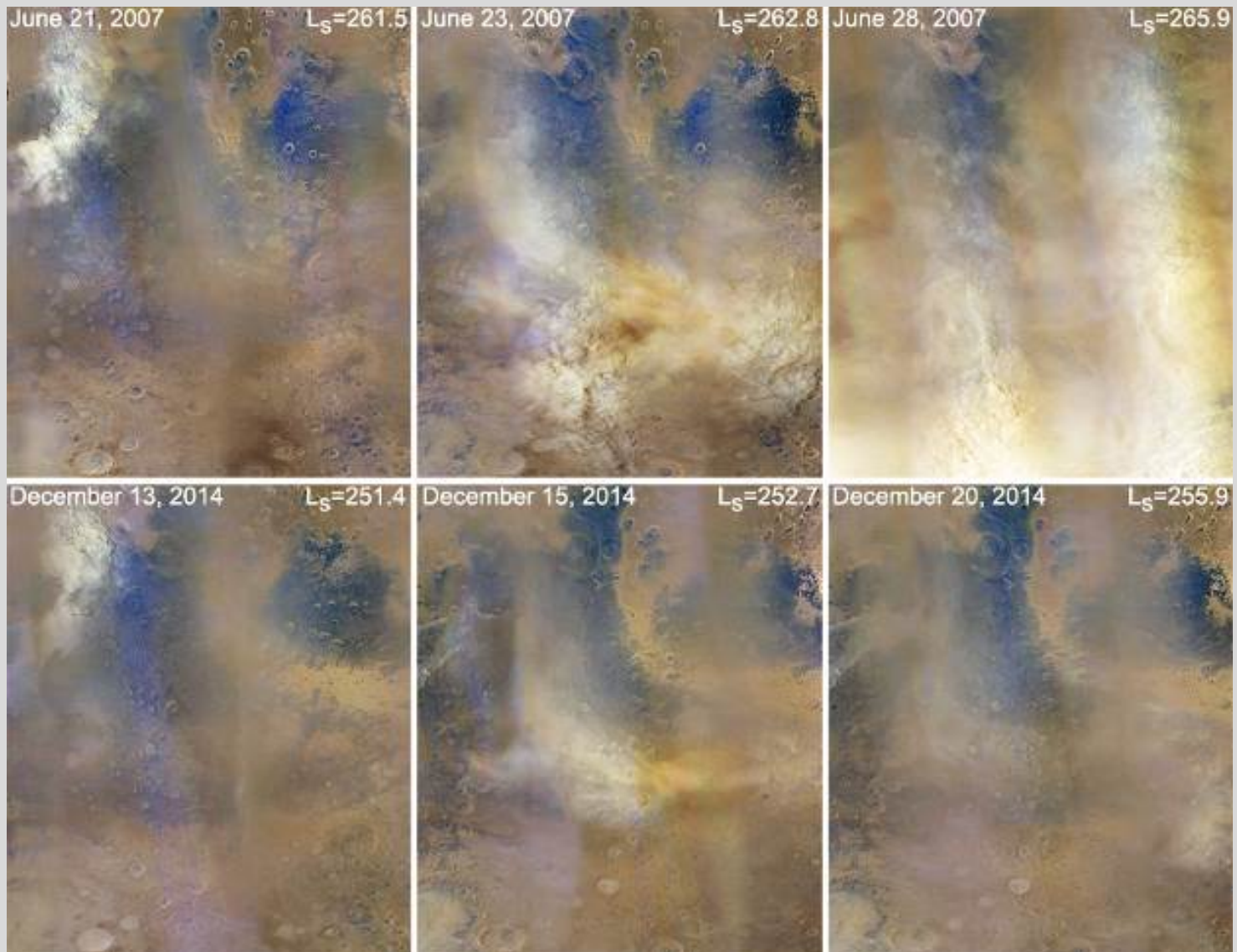
Mars Exploration Program

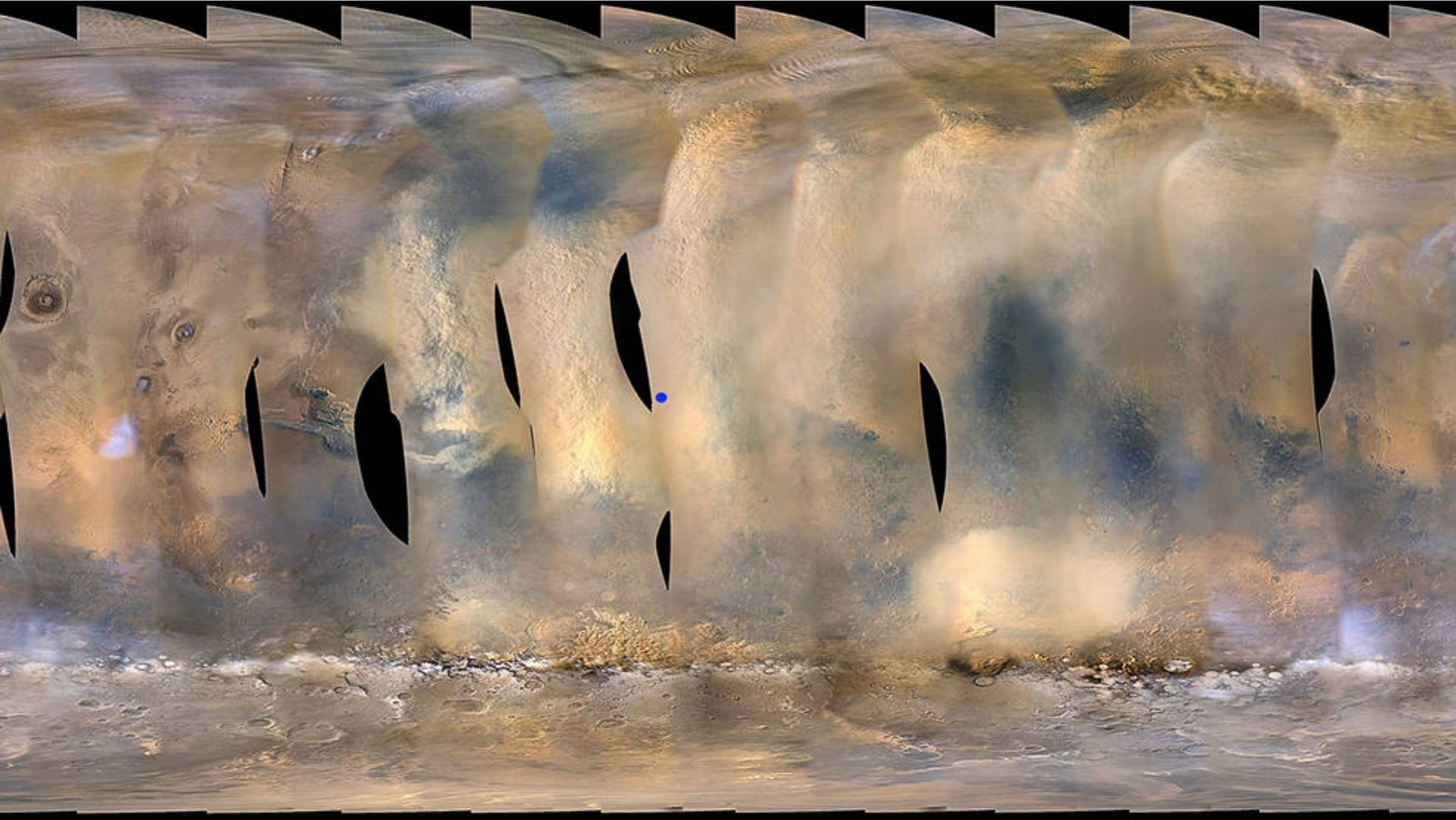




# ***Chaotic Nature of Regional Dust Storm Onset***

*Cantor, in preparation, NASA / JPL / MSSS*



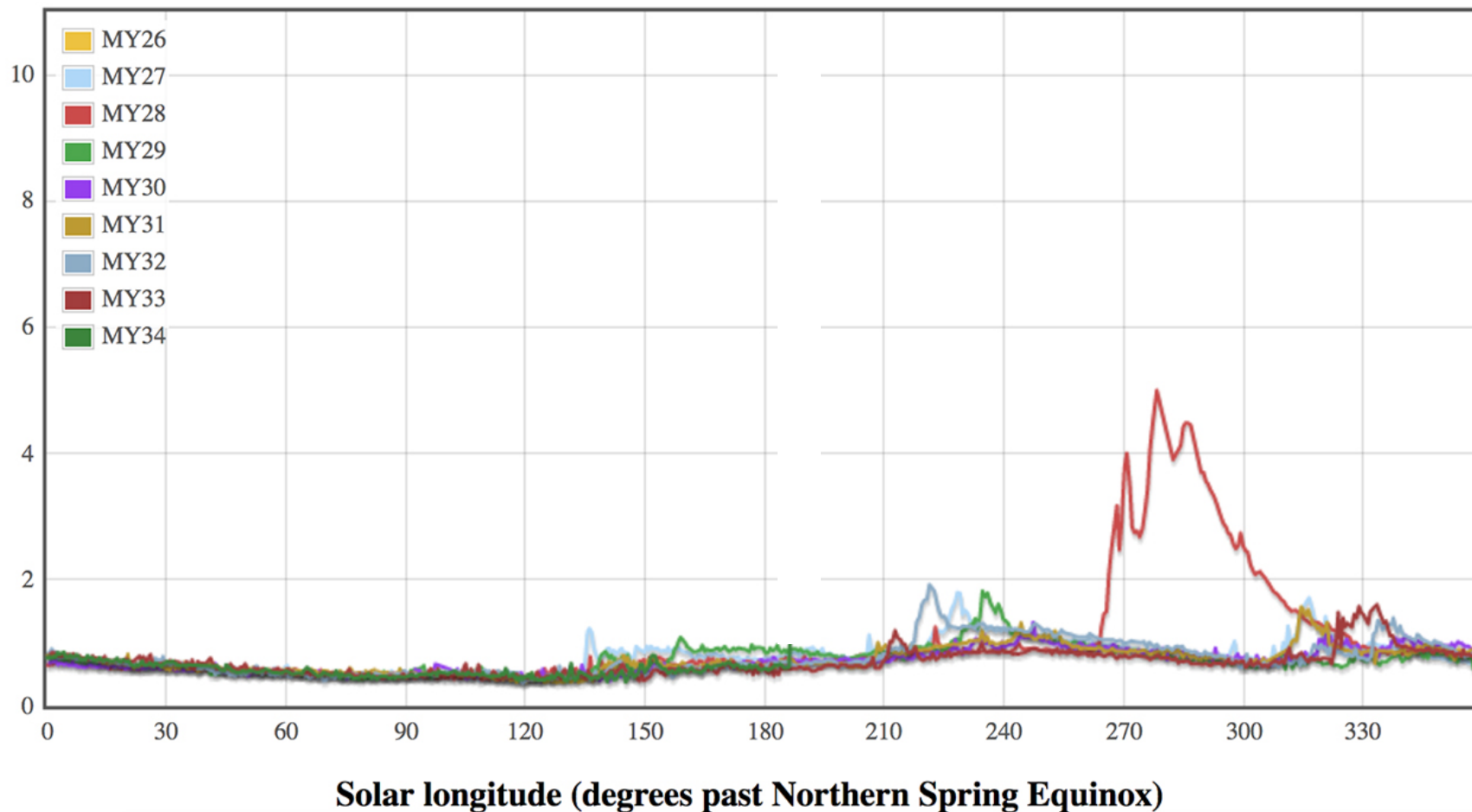


- MER-B

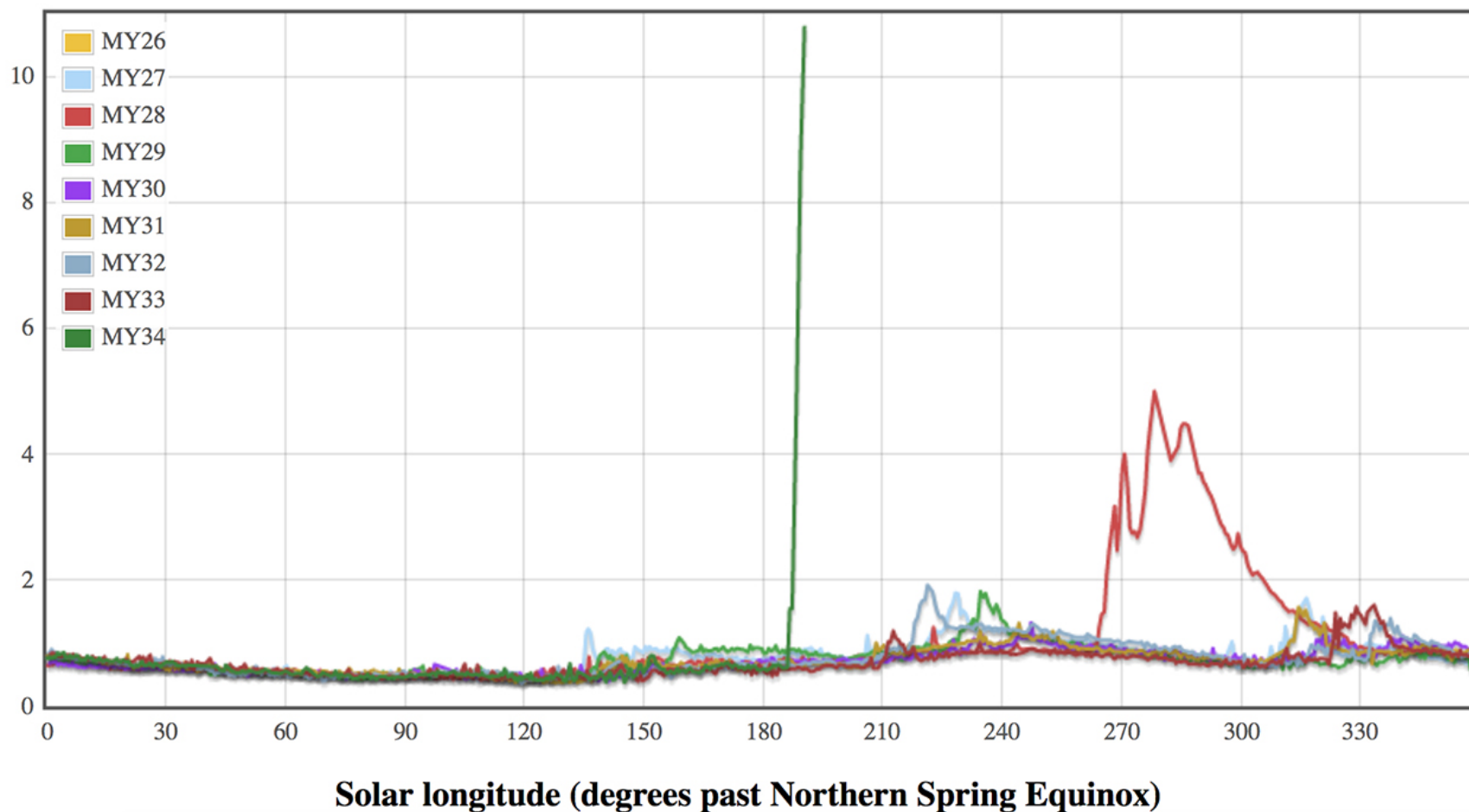
*MRO MARCI / MSSS / JPL / NASA*



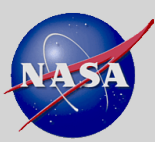
## MER-B seasonal optical depth for all Mars Years (MY)



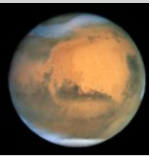
## MER-B seasonal optical depth for all Mars Years (MY)



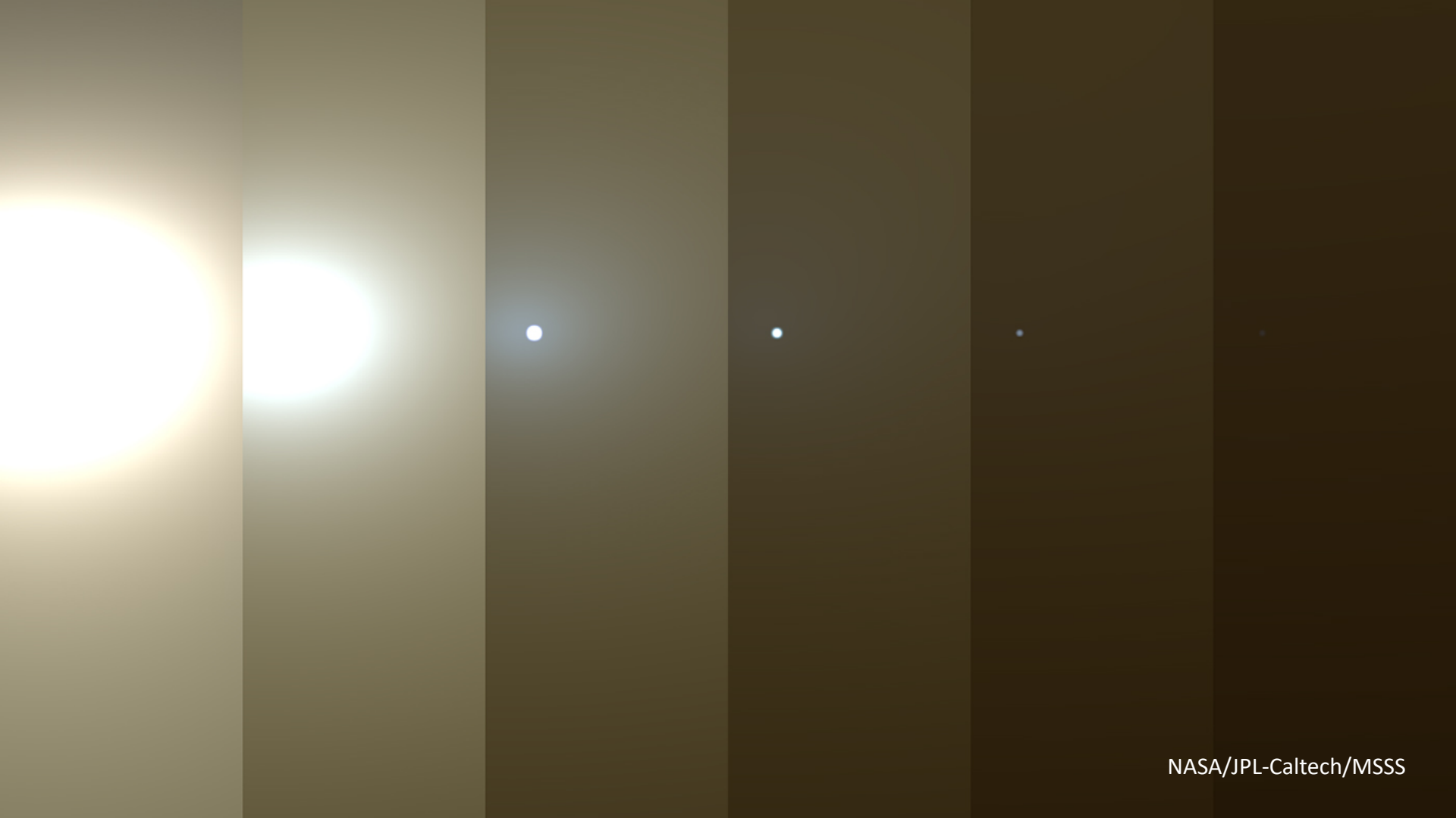




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Space Administration  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA



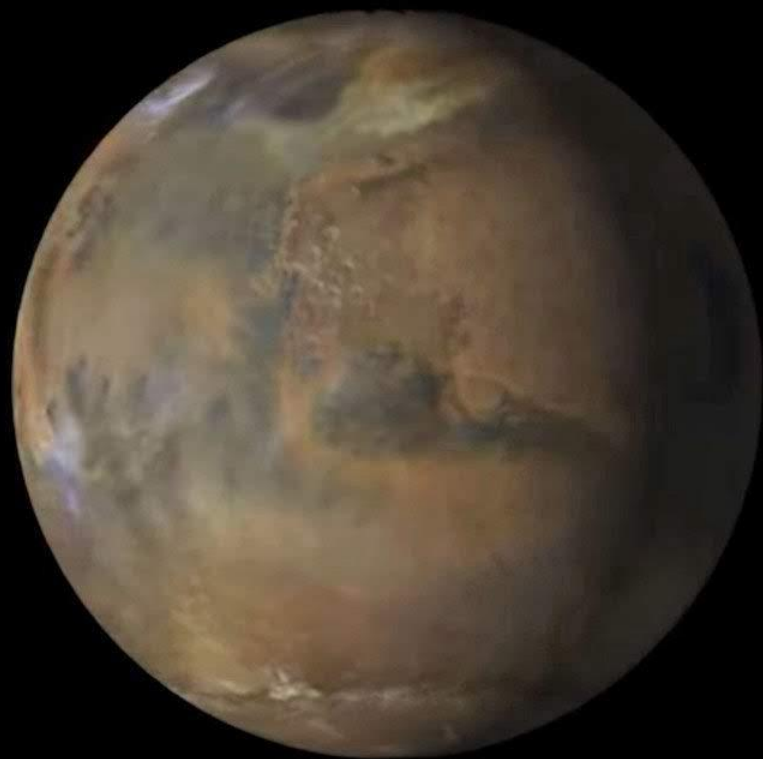
## *Mars Exploration Program*



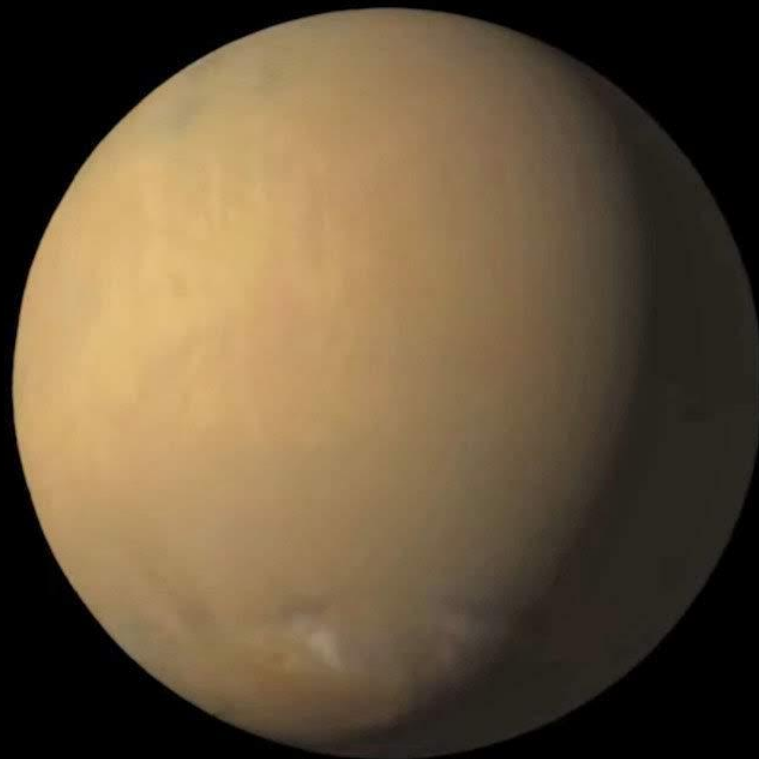


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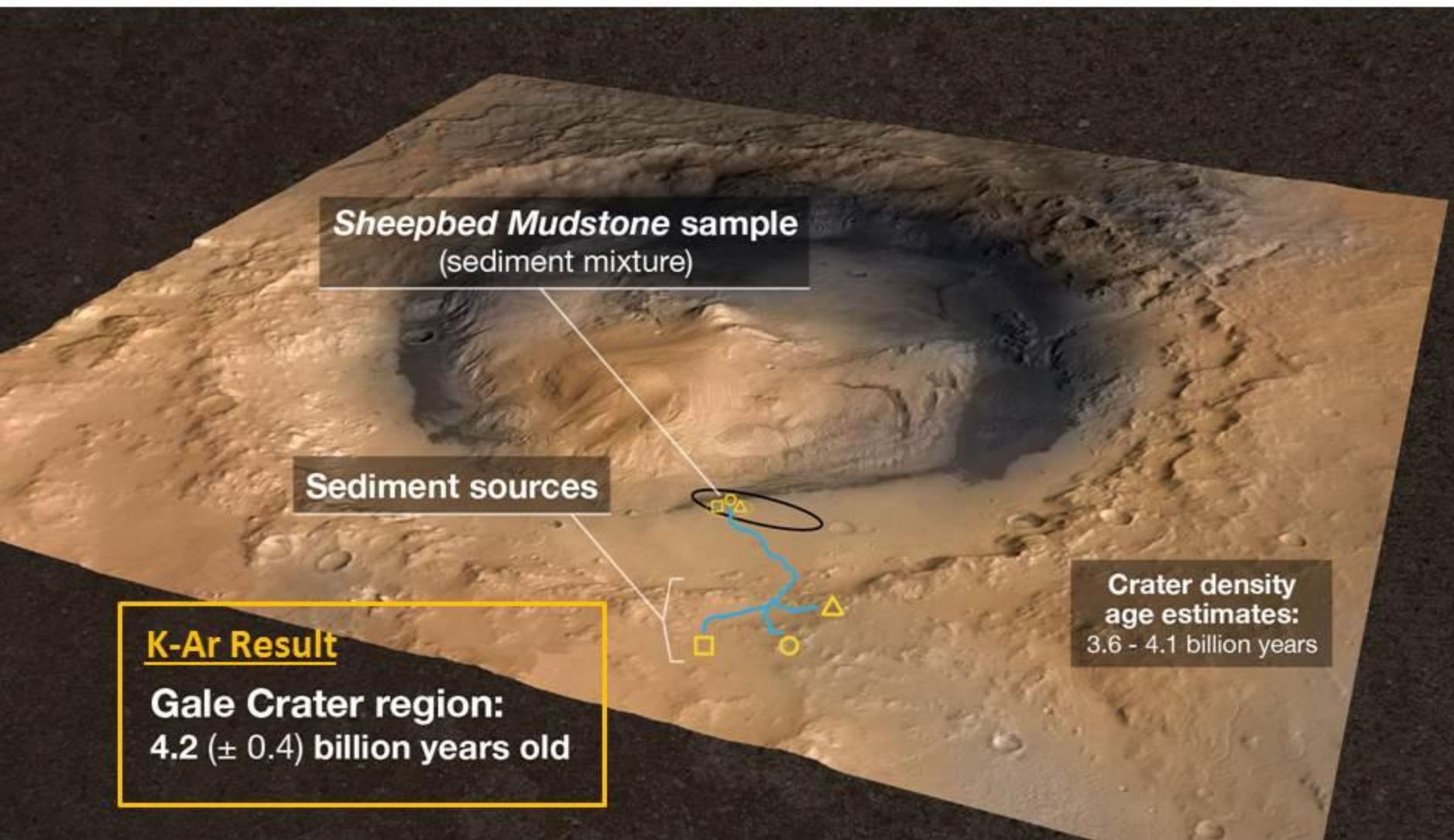
**May 28**



**July 1**



# K-Ar Age Determination of Sheepbed Mudstone





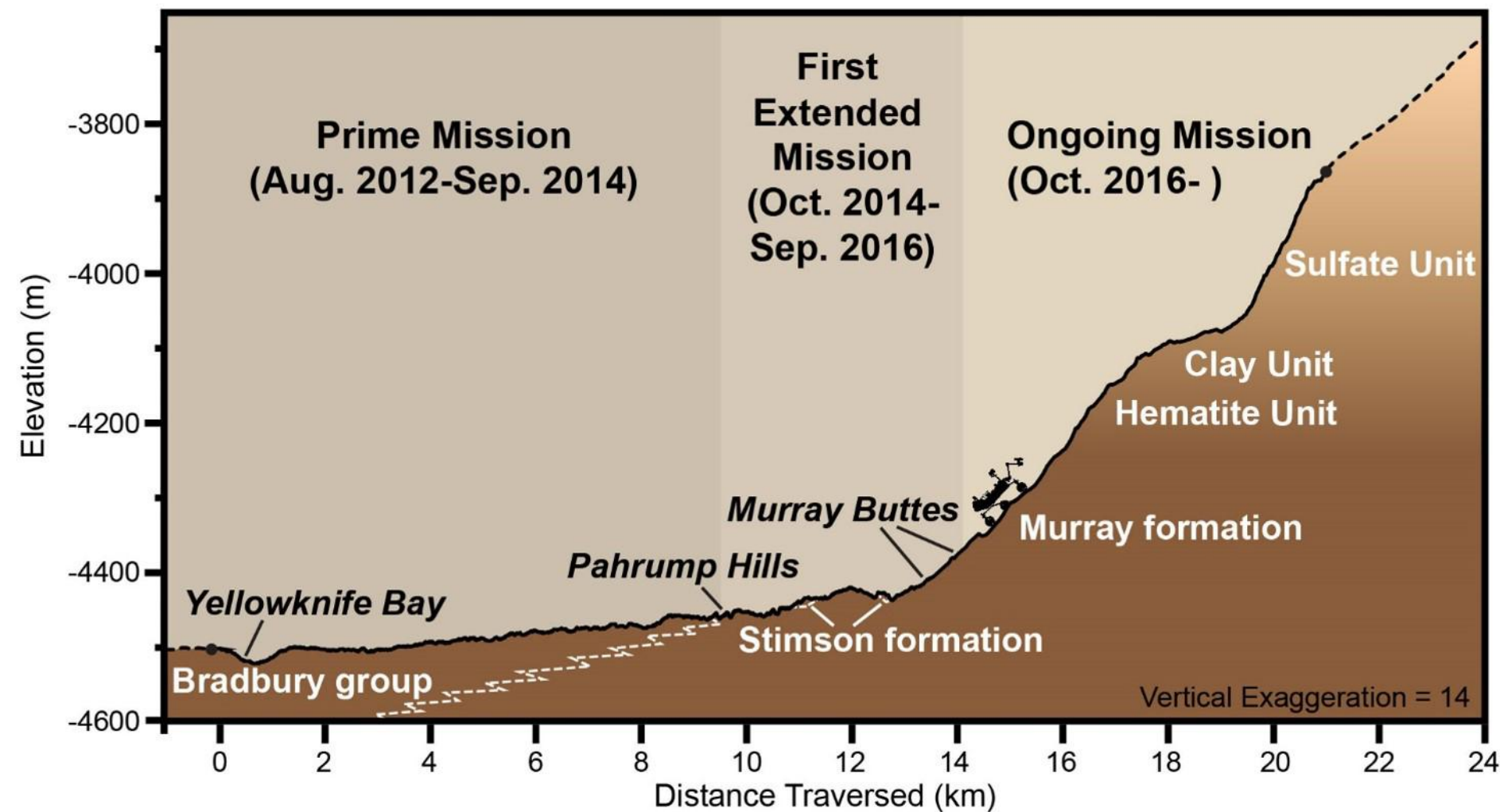
# Did Curiosity find an ancient habitable environment at Yellowknife Bay?

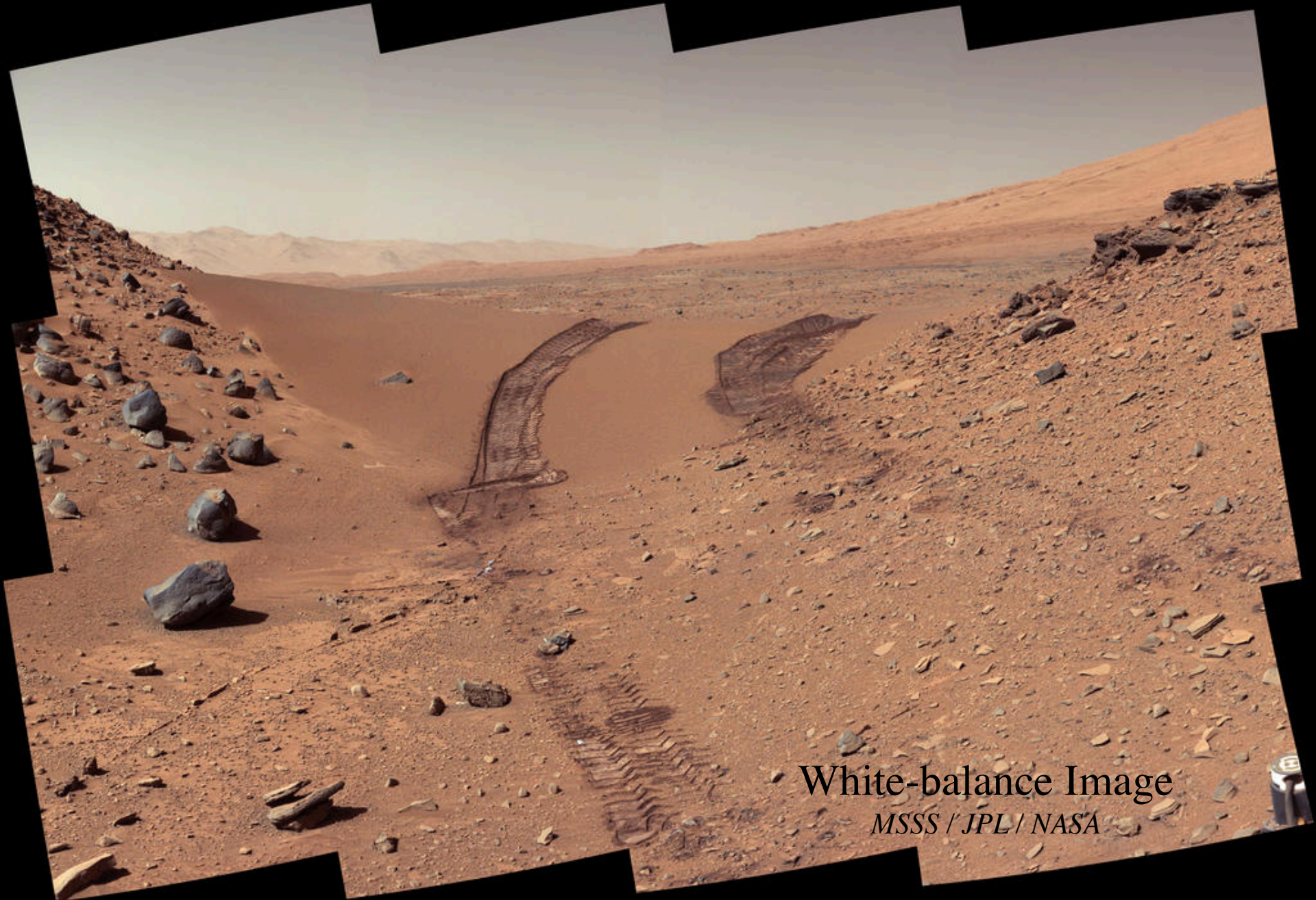
- Relatively neutral pH (Clays, absence of Fe-sulfate)
- Relatively low salinity (low salt abundance, absence of Mg-sulfate)
- Presence of variable redox states (residual primary igneous minerals, magnetite sulfate, sulfide)
- Carbon likely present as poorly crystalline carbonates or heavily degraded organics (CO<sub>2</sub> in SAM EGA)

YES!









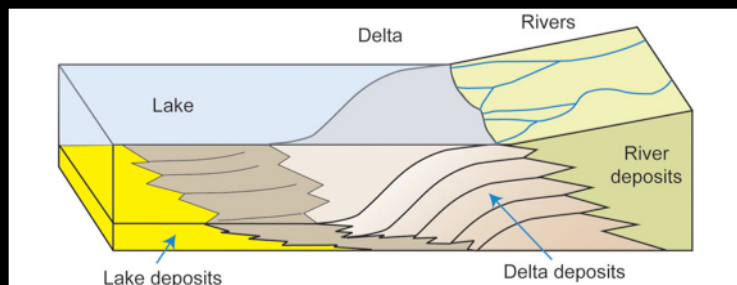
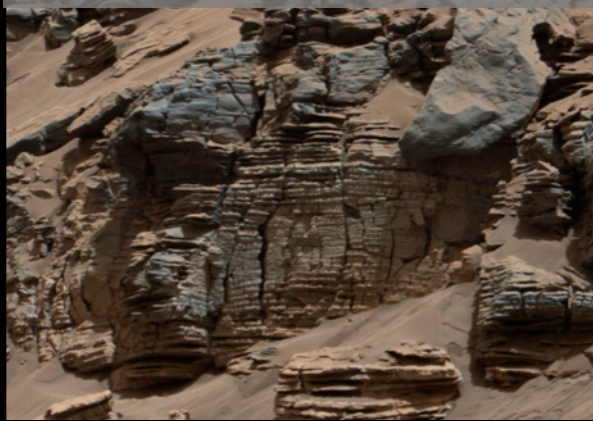
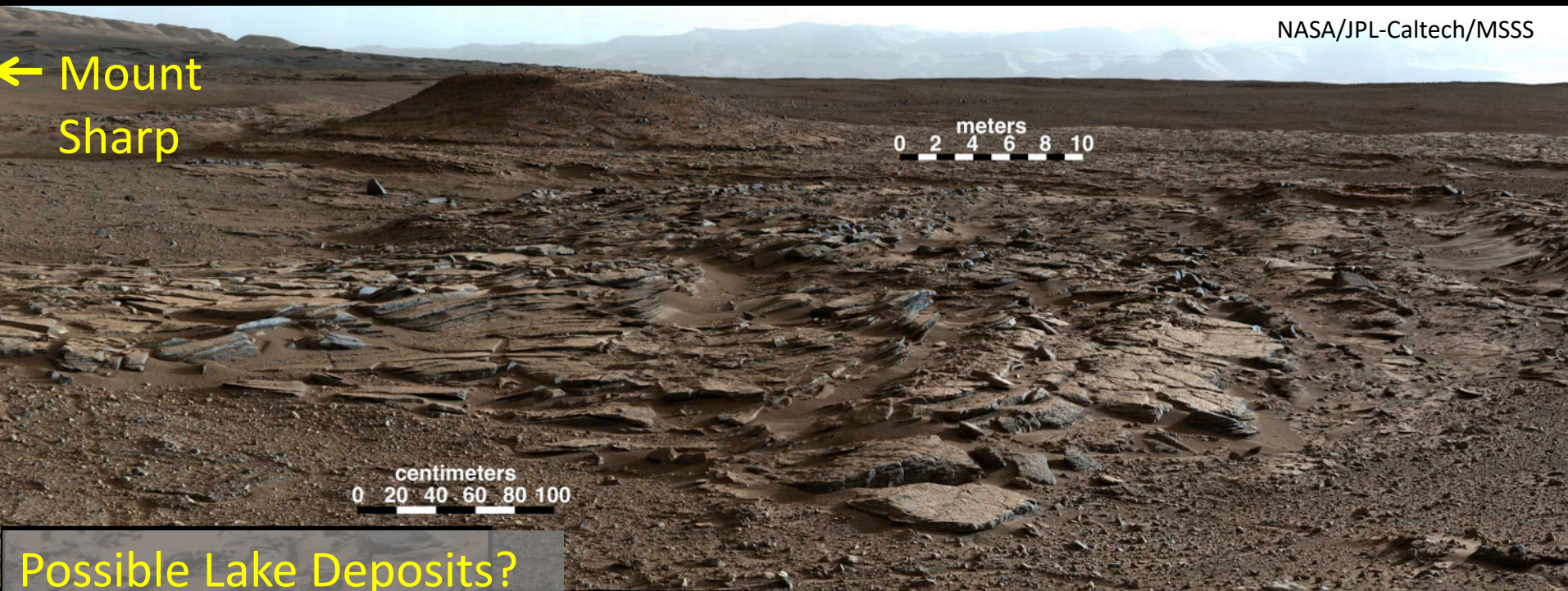
White-balance Image  
*MSSS / JPL / NASA*



Mars Program

NASA/JPL-Caltech/MSSS

← Mount Sharp

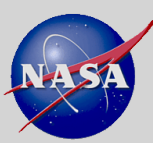


**Hypothesis:** Do southward-tilted sandstone beds on Gale Crater's plains indicate fluvial transport of sediment toward Mount Sharp, building up lake deposits there?



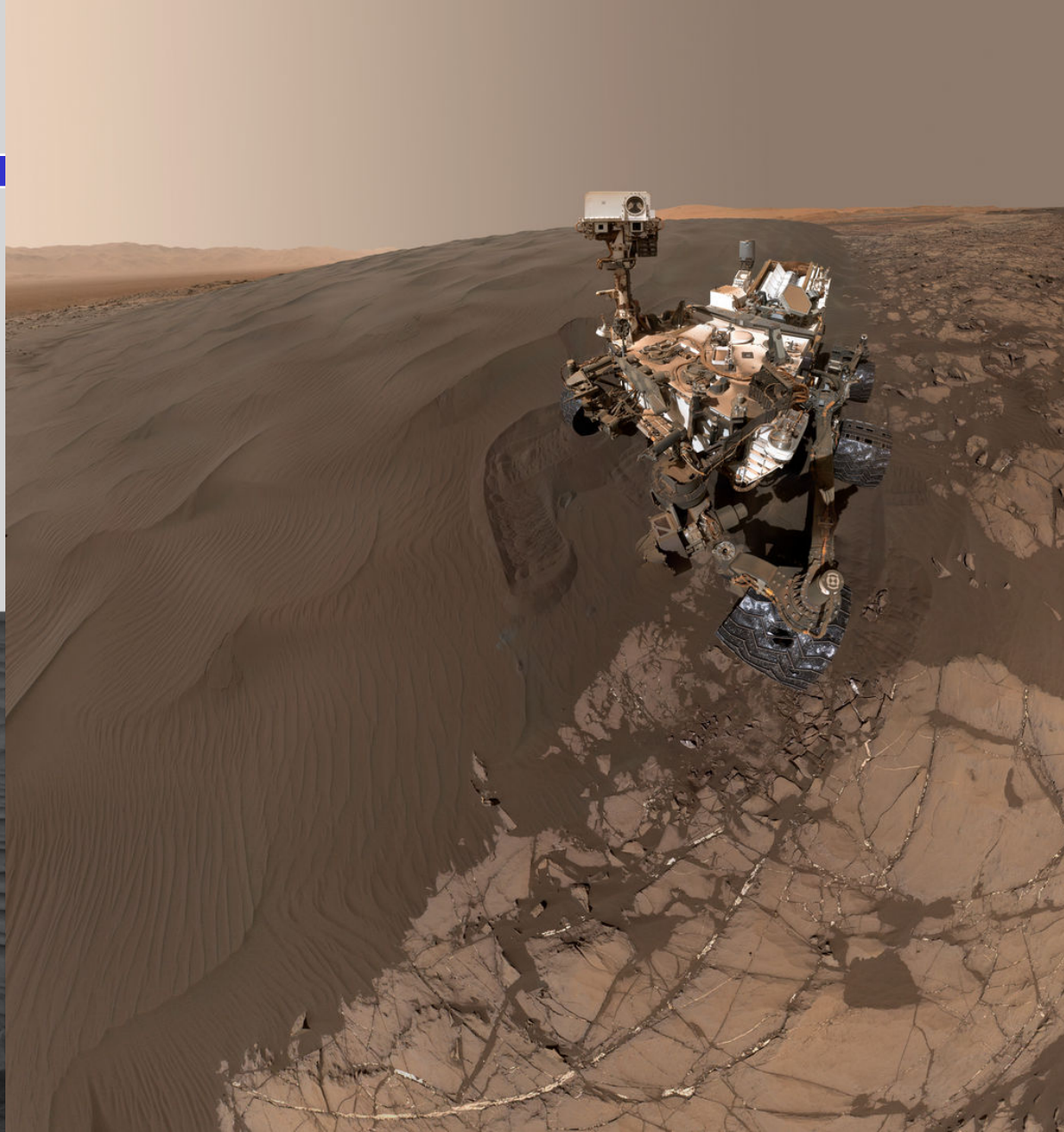






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## *Curiosity Explores the Bagnold Dunes*



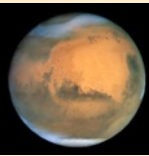
*Curiosity / MSSS / JPL / NASA*

October 14, 2019

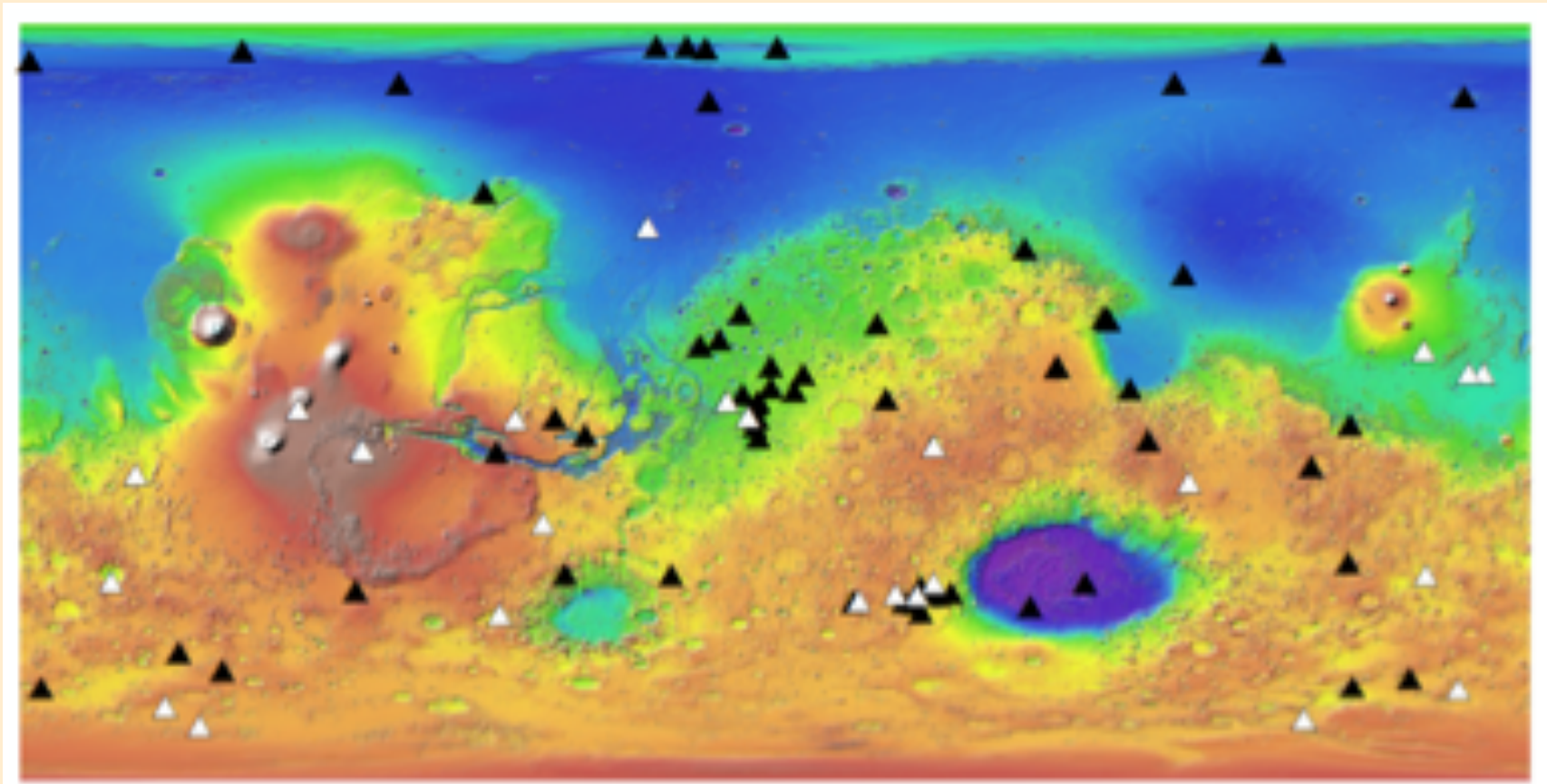
RZ-47  
NASA/JPL-Caltech/MSSS



# Active Sand Dunes on Mars

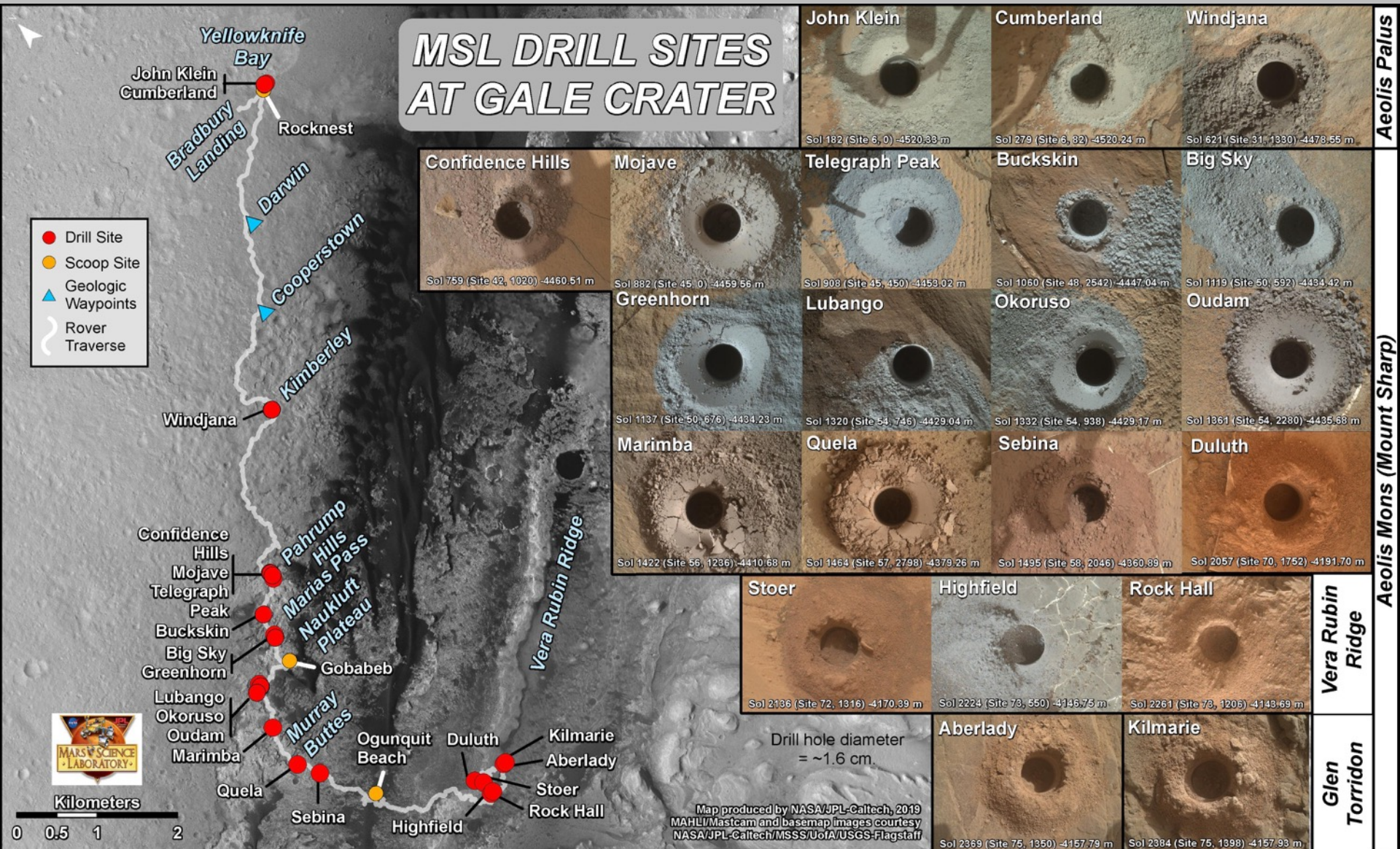


*Mars Exploration Program*

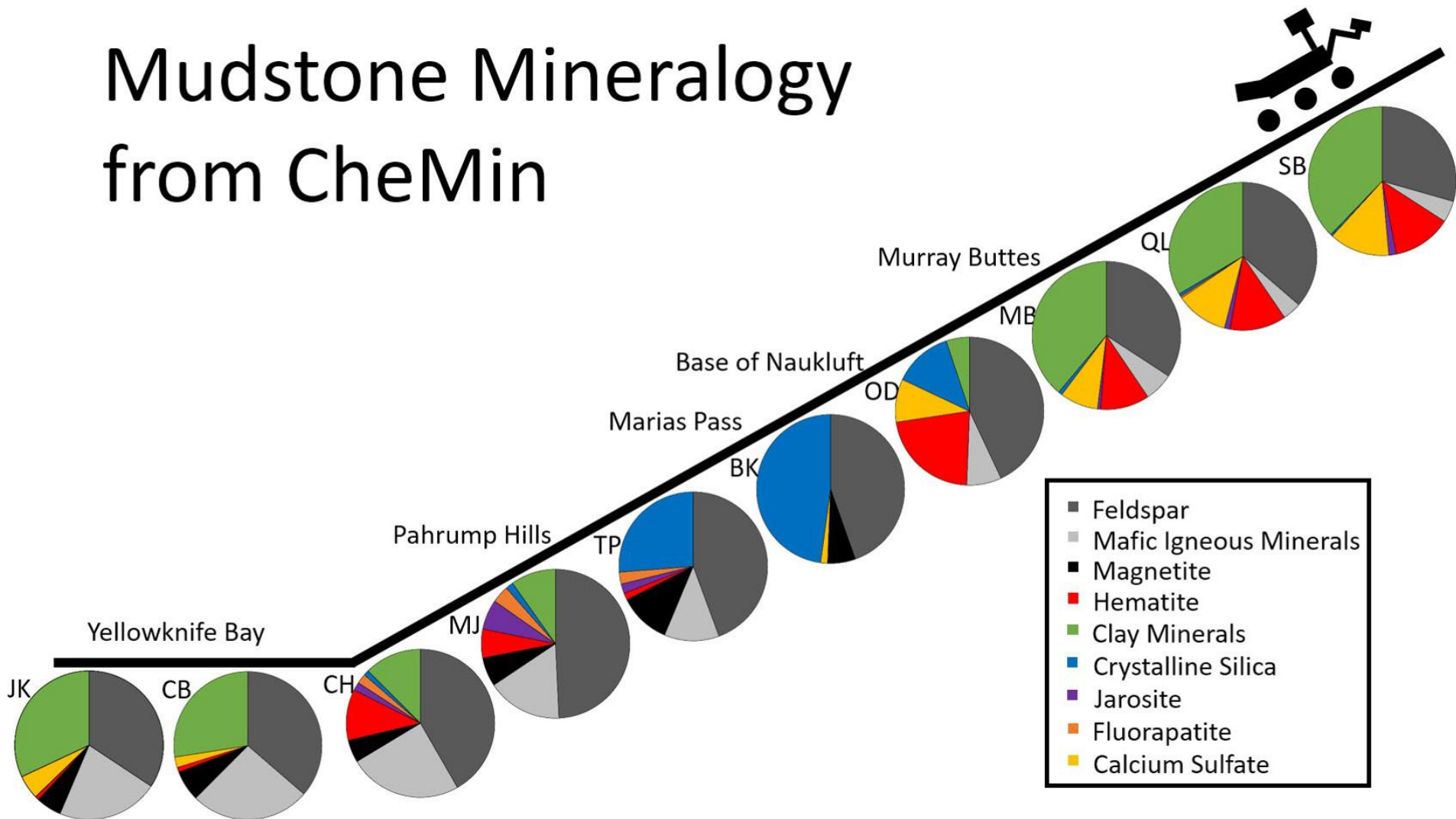


Global map of active dunes; black = motion detected, white = no motion detected so far  
[*Banks et al.*, 2015a].





# Mudstone Mineralogy from CheMin





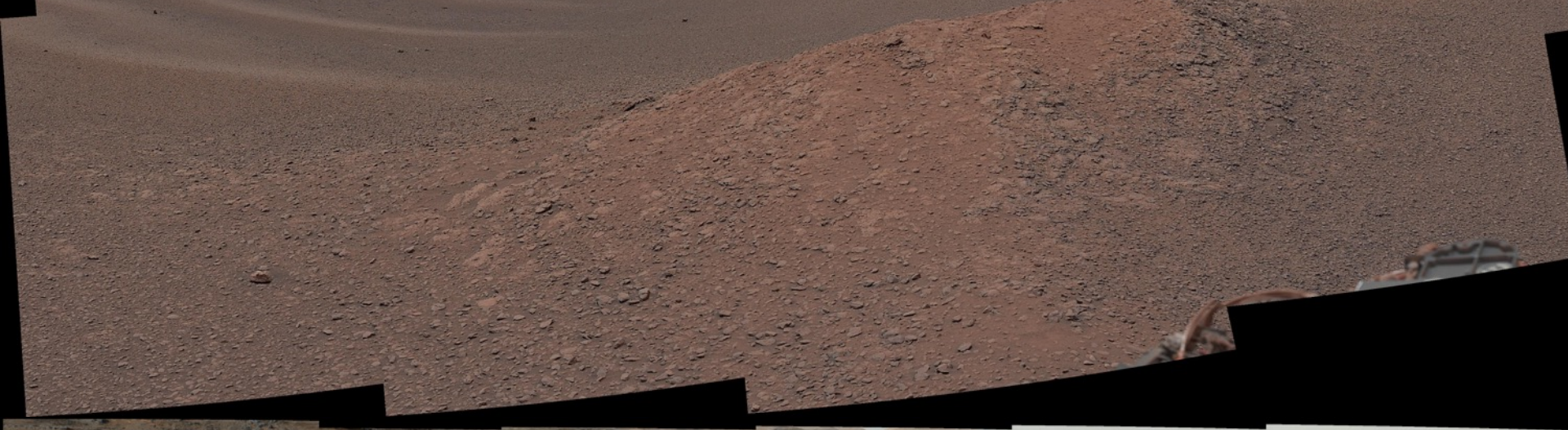
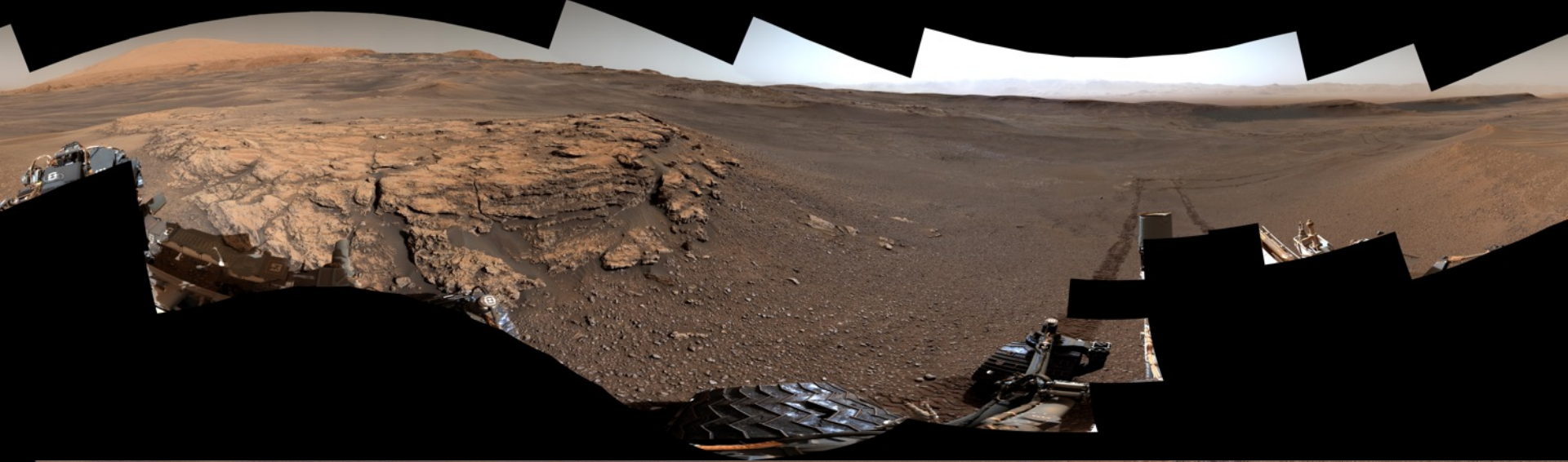


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# Curiosity views Vera Ruben Ridge

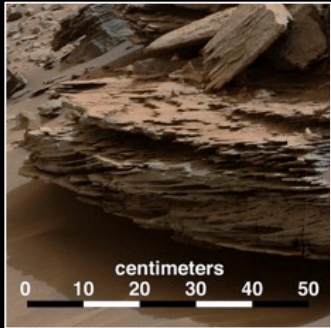






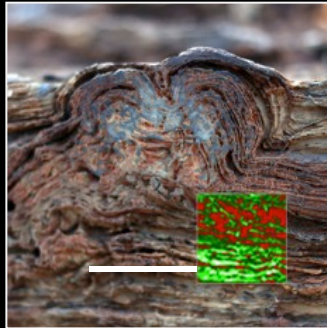


# Mars 2020 Mission Objectives



## GEOLOGIC EXPLORATION

- Explore an ancient environment on Mars
- Understand processes of formation and alteration



## HABITABILITY AND BIOSIGNATURES

- Assess habitability of ancient environment
- Seek evidence of past life
- Select sampling locations with high biosignature preservation potential



## PREPARE A RETURNABLE CACHE

- Capability to collect ~40 samples and blanks, 20 in prime mission
- Include geologic diversity
- Deposit samples on the surface for possible return



## PREPARE FOR HUMAN EXPLORATION

- Measure temperature, humidity, wind, and dust environment
- Demonstrate In Situ Resource Utilization by converting atmospheric CO<sub>2</sub> to O<sub>2</sub>

# The Mars 2020 Rover: Robotic Field Geologist + Astrobiologist

## SAMPLING MARS

In 2020, NASA plans to send a rover to Mars to collect and store tubes of rock and dirt. The plutonium-powered vehicle will have seven instruments and may also carry a helicopter.

### RIMFAX



A ground-penetrating radar to explore beneath the surface.

A plutonium power source supplies electricity to the rover.

### SUPERCAM



A laser blaster that can investigate chemical compositions of Martian rocks and dirt from a distance.



### HELICOPTER

The rover may carry a helicopter that would fly through the thin atmosphere and scout out the path ahead.

### MASTCAM-Z

A zoomable panoramic camera.

### MEDA



The rover's weather station, to measure temperature, wind speed and other meteorological factors.

### SHERLOC

An ultraviolet spectrometer to study mineralogy and chemistry. (Its camera is named WATSON.)



### PIXL

An X-ray spectrometer for probing the chemical composition of rocks and dirt close up.

### ROBOTIC ARM

The rover arm can extend outwards to make scientific measurements and gather samples. Its instruments can study, in detail, an area about the size of a postage stamp.

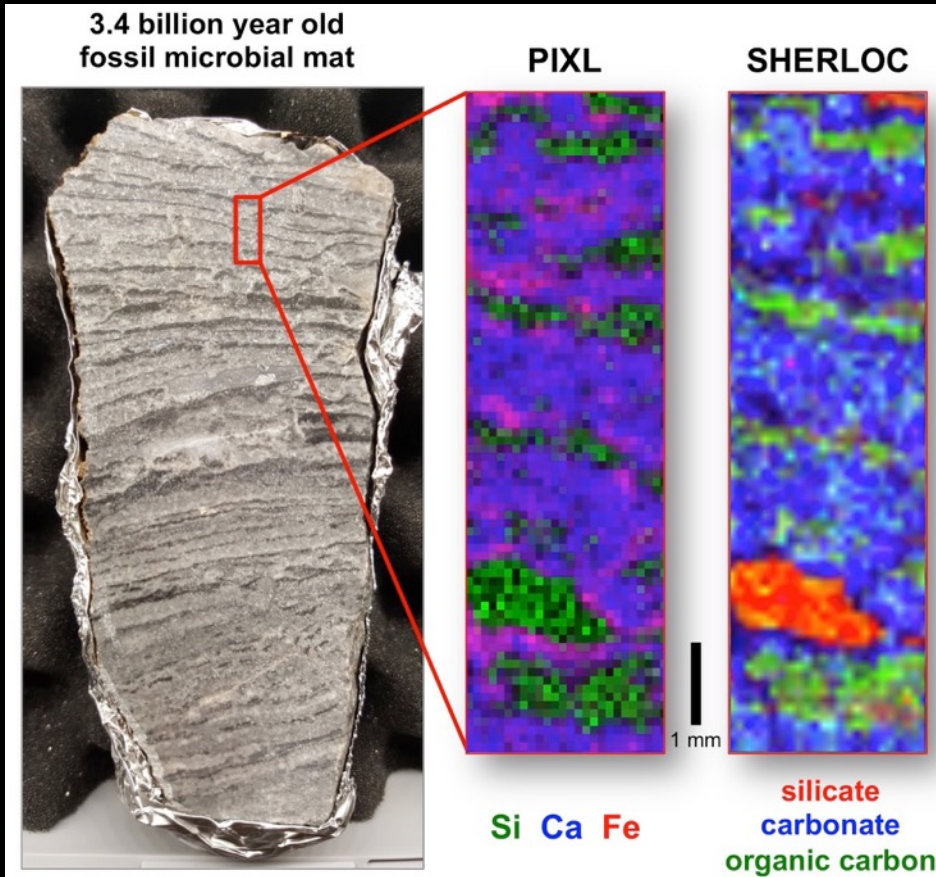
### MOXIE

An instrument to produce oxygen from carbon dioxide in the Martian atmosphere, as a test for creating resources for future astronauts.

Credit: *Nature Magazine*



# Seeking Signs of Ancient Life



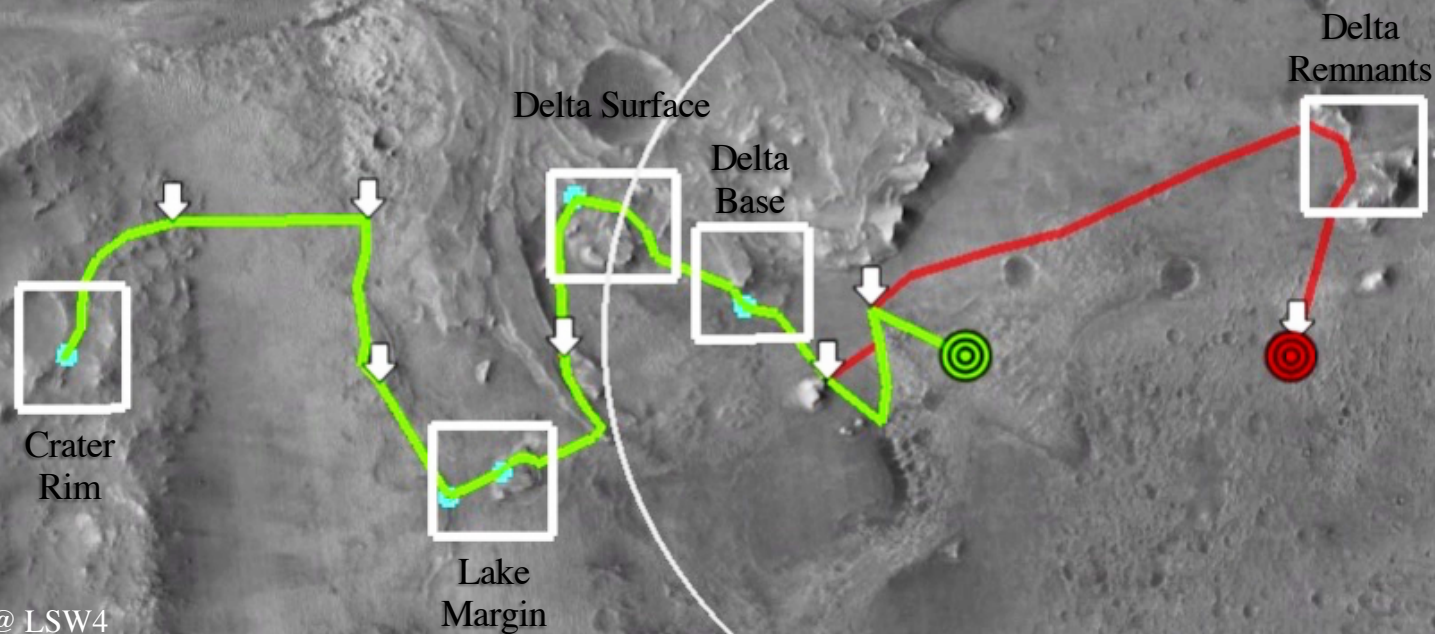
Mars 2020 can recognize potential biosignatures as lifelike patterns in the exploration environment.

- Concentrations of biologically important elements, minerals, and/or molecules
- Spatially associated with biologically suggestive morphologies

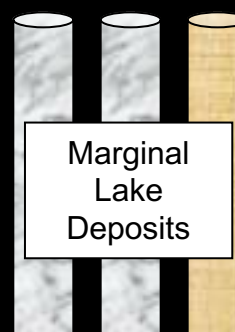
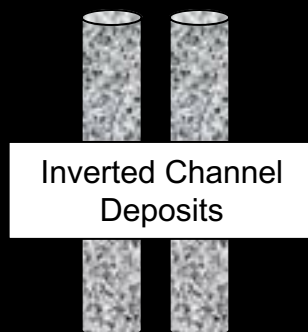
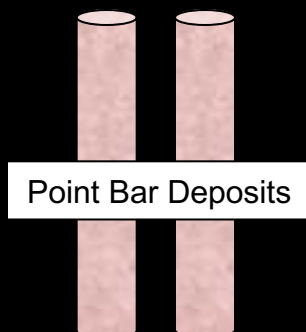
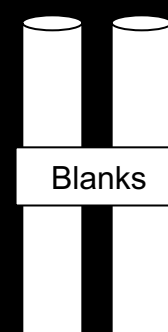
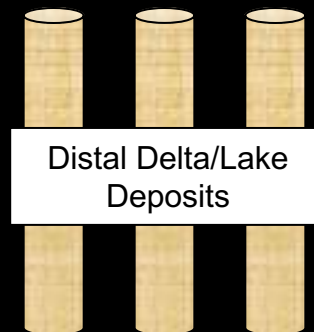
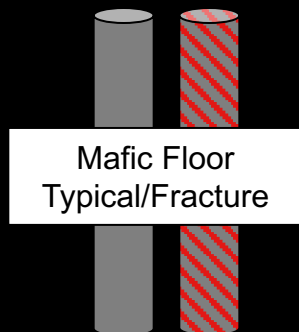
*Confirmation of a biosignature likely requires analysis of returned samples.*

Option 1: Eastern Landing + Delta Remnants (15 km traverse)

Option 2: Western Landing + Crater Rim (15 km traverse)





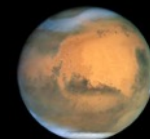


# Returned Sample Science Objectives

- **LIFE** – Determine if fine-grained lower delta strata and carbonate-bearing units contain biosignatures, and show evidence for past martian life
- **GEOCHRONOLOGY** – Seek to determine age of basement materials and Isidis impact, Jezero impact, and carbonates from detrital sediments and in-situ samples. Constrain fluvio-lacustrine history.
- **CRATER CHRONOLOGY** – If volcanic, determine the absolute age of Mafic Floor unit using multiple geochronometers and combine with crater count statistics to place quantitative bounds on relative age dating of Martian surfaces
- **IGNEOUS HISTORY** – Determine igneous petrogenesis of Mafic Floor unit, igneous detrital grains, and crater rim basement using petrology and isotope geochemistry
- **CARBON CYCLE** – Investigate the Martian carbon cycle through geochemical analysis of detrital deltaic, lacustrine precipitates, and in situ alteration-derived carbonates
- **LAKE CHEMICAL EVOLUTION** – Determine the chemistry/temperature/timing of the Jezero lake through isotope geochemistry analysis of fine-grained delta succession and bound water/fluid inclusions
- **EARLY MARS CLIMATE** – Determine the timing of valley network activity from deltaic samples and bounding units, atmospheric density, and escape rates from carbonate isotopes



# Sample Return is the logical Next Step



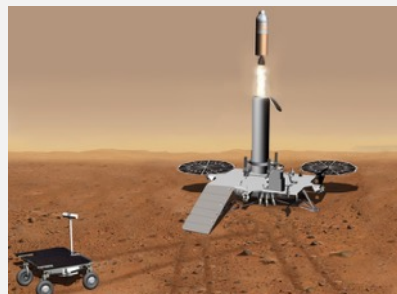
Mars Exploration Program

- The 2011 Planetary Decadal Survey (*Visions & Voyages*):
  - “The return of samples allows for the analyses of elemental, mineralogic, petrologic, isotopic and textural information using state-of-the-art instrumentation in multiple laboratories.”
    - Includes the ability to conduct follow-up experiments with ever-advancing tools



**Sample Caching Rover  
(Mars 2020)**

- *Sample acquisition and caching*



**Sample Retrieval  
Lander (concept)**

- *Fetch Rover*
- *Orbiting Sample container (OS)*
- *Mars Ascent Vehicle*



**Earth Return  
Orbiter (concept)**

- *Rendezvous and On-Orbit Capture System*
- *Earth Entry Vehicle*



**Mars Returned Sample  
Handling**

- *Sample Receiving Facility*
- *Curation*
- *Sample science investigations*

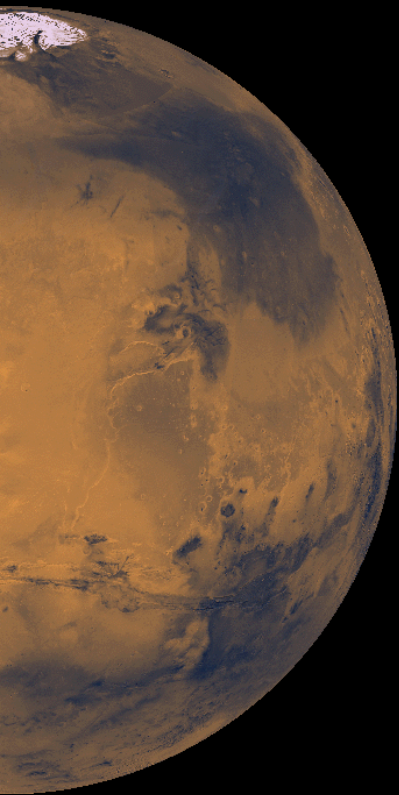
**Flight Elements**

**Ground Element**

*Pre-Decisional—For Planning and Discussion Only*

# ***What have we learned?***

***Mars is a complex planet which continues to change even today***



- Mars was once habitable—was it ever inhabited?
  - Habitability of many areas was intermittent, as water came and went over the first half of Mars history.
  - If there is life today, it is probably in the subsurface.
- Mars has lost ~70% of its ancient atmosphere.
  - Much of its water was lost to space or trapped as ice on and beneath its surface.
  - Water is not stable as a liquid on the surface today.
- Mars has resources that could be utilized *in situ*:
    - Hydrated minerals and water ice; atmospheric CO<sub>2</sub>
  - Mars has challenges:
    - Radiation; meteor impacts, dust storms

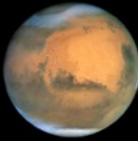




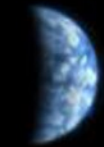
Sunset on Mars  
*MSSS / JPL / NASA*



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## *Mars Exploration Program*



Earth & Moon from Mars Orbit  
*MRO HiRISE / U. Arizona / JPL / NASA*